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The recent history of the machine tool
industry and the effects of
technological change



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Abstract – Rather long re-investment cycles of about 15 years have created the notion that innovation in the machine tool industry happens incrementally. But looking at its recent history, the integration of digital controls technology and computers into machine tools have hit the industry in three waves of technology shocks. Most companies underestimated the impact of this new technology. This article gives an overview of the history of the machine tool industry since numerical controls were invented and introduced and analyzes the disruptive character of this new technology on the market. About 100 interviews were conducted with decision-makers and industry experts who witnessed the development of the industry over the last forty years. The study establishes a connection between radical technological change, industry structure, and competitive environment. It reveals a number of important occurrences and interrelations that have so far gone unnoticed. The findings are supported by a worldwide qualitative survey in which statements from 59 companies were collected.

Index Terms -Machine tools, numerical controls, history, strategy, innovation, technological change, technology shock.

A. *The machine tool industry after World War II*

While contributing to only about 2% of the total industrial production¹, the machine tool industry is fundamental for the investment goods industry. It provides the principal industrial equipment base for the manufacturing industries. The machine tool industry developed and matured with its main markets, the machinery industry, the automotive industry, the defense and aerospace industry and other investment goods industries². By the turn of the Twentieth Century, the US had developed a strong position in the world's export markets through a well-organized network of sales agents. The world wars even strengthened the position of US manufacturers. Germany, which had been the world's largest exporter in 1910³, dropped behind. After the Second World War, much of the industry in Germany had been dismantled⁴. The United Kingdom, which had led the development of machine tools since the industrial revolution⁵, was in the fortunate position to have had a manufacturing infrastructure that was fairly untouched by the war.

Destruction of the rest of Europe's manufacturing industries made the availability of equipment a fundamental part in manufacturing companies' post war strategies⁶. Equipment was badly needed at almost any price. This allowed the industry to grow at a steady pace of approximately 10% per annum from 1950 – 1970.

Innovation was incremental until the 1970s when the occurrence of numerical controls upset the industry and caused considerable problems to established companies. The emergence of numerical control caused a major discontinuity in the US machine tool industry's traditional product line. Through this one invention the industry was thrust into

¹ Joao O. Rendeiro, "How the Japanese Came to Dominate the Machine Tool Business," *Long Range Planning* 18, no. 3 (1985): 62-67.

² BCG, "Europastudie für ausgewählte Zielländer - Dokumentarband," (Verein Deutscher Werkzeugmaschinenfabriken e.V. -VDW, 1990).

³ Robert Mazzoleni, "The Agency System in the International Distribution of U.S. Machine Tools, 1900 - 1915: Social Norms and Contracts," *Business and Economic History* 27, no. 2 (1998): 420 - 430.

⁴ For the effect of the Second World War and the subsequent "dismantling" of most of the production capacities of Germany see pp. 465 - 488 in Günter Spur, *Vom Wandel der industriellen Welt durch Werkzeugmaschinen*, ed. Verein Deutscher Werkzeugmaschinenfabriken e.V. (München, Wien: Carl Hanser Verlag, 1991).

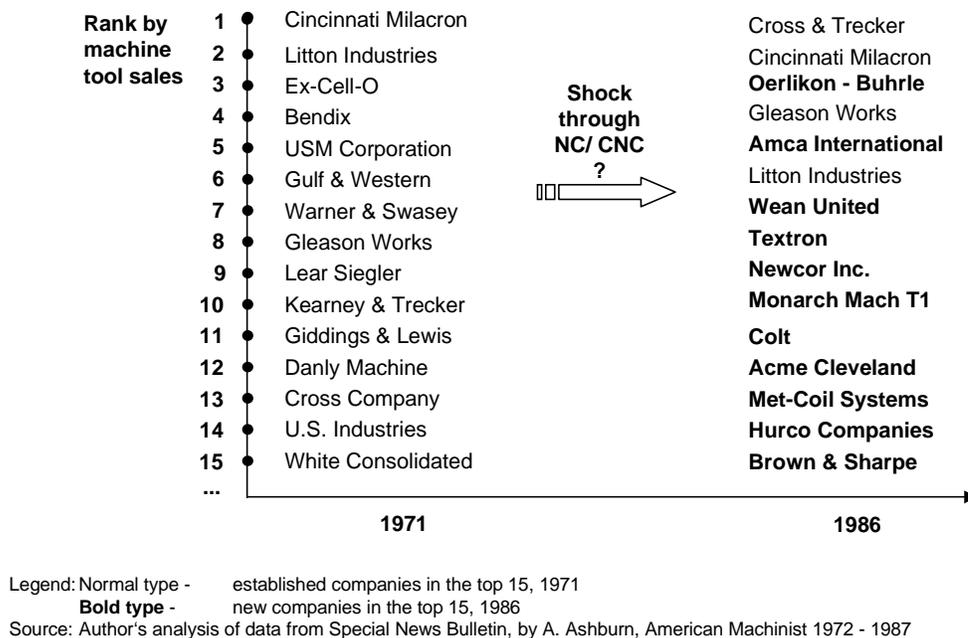
⁵ The history of machine tools and the machine tool industry from 1700 to 1910 is described in W. Steeds, *A History of Machine Tools 1700 - 1910* (Oxford: The Clarendon Press, 1969). For an overview of the history until around 1980 see E. Sciberras and B.D. Payne, *Machine Tool Industry*, ed. The Technical Change Centre, 1 ed., vol. 1, *Technical Change and International Competitiveness* (London: Longman Group Limited, 1985).

⁶ Mr. Passemard, Renault Automation, Industry-Expert-Interview-Series, "Interview Series," (2000-2001).

the age of digital electronic machine-tool controls, and opportunities were created for a variety of new products and business models in the market place. Some companies were able to transform their businesses, many not.

What Christensen had observed for the rigid disk drive industry⁷, happened in the machine tool industry in the face of radical technological change. Many of the then established companies lost their positions, went bankrupt, were taken over or left the market. At the same time as technological change occurred the US producers' market for machine tools was in turbulence - from 1971 to 1986 only 5 of the 15 largest companies were able to maintain their position amongst the top 15⁸ (see figure below).

US Machine Tool Industry: Turbulence in the market



⁷ Clayton M. Christensen, "The Rigid Disk Drive Industry: A History of Commercial and Technological Turbulence," *Business History Review* 67, no. 4 (1993): 531-558. Another example is John M. de Figueiredo and Margaret K. Kyle, "Surviving the Gales of Creative Destruction: The Patterns of Innovative Activity in the Desktop Laser Printer Industry," *MIT Sloan Working Paper* (2000).

⁸ Ranking by revenue from Anderson Ashburn, "Blue Bulletin," (AMT - The Association for Manufacturing Technology, American Machinist, 1972-2000).

Between 1972 and 1987, the US lost its leading position as the biggest producer of machine tools to Germany and the new entrant Japan (see figure below), as well as statistically to the Soviet Union⁹.

Since World War II the US had emerged as the leading producer of machine tools with up to 30% of the world market in the post war years¹⁰. In the late 1960s though, the US influence dropped. Although the consumption of machine tools in the US was growing¹¹, the US manufacturer's share of the world market had decreased to 15% by 1970, behind Germany, which held between 15 to 20%. Germany was also leading once again in terms of export volume. By 1977 Germany controlled 30% of the world's export trade¹². This situation lasted until 1980 when Japan – parallel to the introduction of computers into numerical controls - conquered 20% of the world market. The US share dropped further to around 10%¹³ and also lost control over its home market.

Likewise at the same time the British share of the world market fell from 8% in 1971 to 5% in 1977, and to 3% in 1981¹⁴; employment fell from 81,000 in 1960 to 62,000 in 1976. Machine tool imports were growing between 1971 and 1982 from 30% to 61% of domestic consumption¹⁵.

On the other hand, the Swiss companies were – despite the contemporaneous crisis in the watch industry¹⁶, their most important home market - able to retain their share of the world market. However, in general, European companies lost in importance.

⁹ Clifford W. Fawcett and Dan Roman, "Industry Overview for the Purchaser of Machine Tools," *Journal of Purchasing and Materials Management*, Fall 1976 (1976): 8-14.

¹⁰ See foreword of Francis J. Reintjes, *Numerical Control: Making a New Technology*, ed. J.R. Crookall, Milton C. Shaw, and Nam P. Suh, vol. 9, *Oxford Series on Advanced Manufacturing* (New York, Oxford: Oxford University Press, 1991).

¹¹ For details refer to Jeffrey Harrop, "Crisis in the Machine Tool Industry: A Policy Dilemma for the European Community," *Journal of Common Market Studies* 24, no. 1 (1985): 61 - 76.

¹² S.T. Parkinson, "Successful New Product Development - An International Comparative Study," *R&D Management* 11, no. 2 (1981): 79-85.

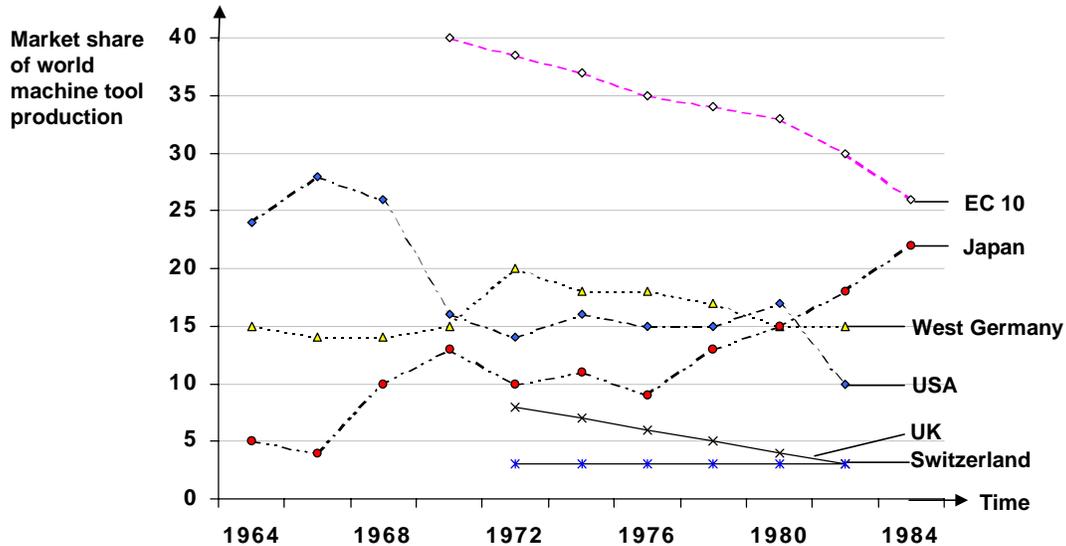
¹³ Market share data is taken from AMT, "World Market Shares," *American Machinist* (1984): 2.

¹⁴ Metalworking Production, *The Fifth Survey of Machine Tools and Production Equipment in Britain* (London: Morgan Grampian, 1983).

¹⁵ Deborah Arnott, "The British Machine Tool Trauma," *Management Today* (1983): 72 - 80.

¹⁶ Lukas Weiss, Tornos Bechler, Industry-Expert-Interview-Series, "Interview Series."

Development of world market shares at the time of technological change



Source: Own depiction based on data from American Machinist, Feb. 3, 1984, p. 2, Metalworking Production, and own estimates

After 1973, the economies of the largest industrialized countries were characterized by slow growth. Users of machine tools were looking for ways to increase the efficiency of their operations. Therefore NC machine tools, which offered improved flexibility and reduced costs, were very welcome. In the US and Western Europe there was a dramatic rise in demand for NC machines at lower cost¹⁷. In the interview series, decision makers, whose companies were not “first to market”, stated that their introduction of NCs had been the reaction to demand-pull - customers asking for the NC features.

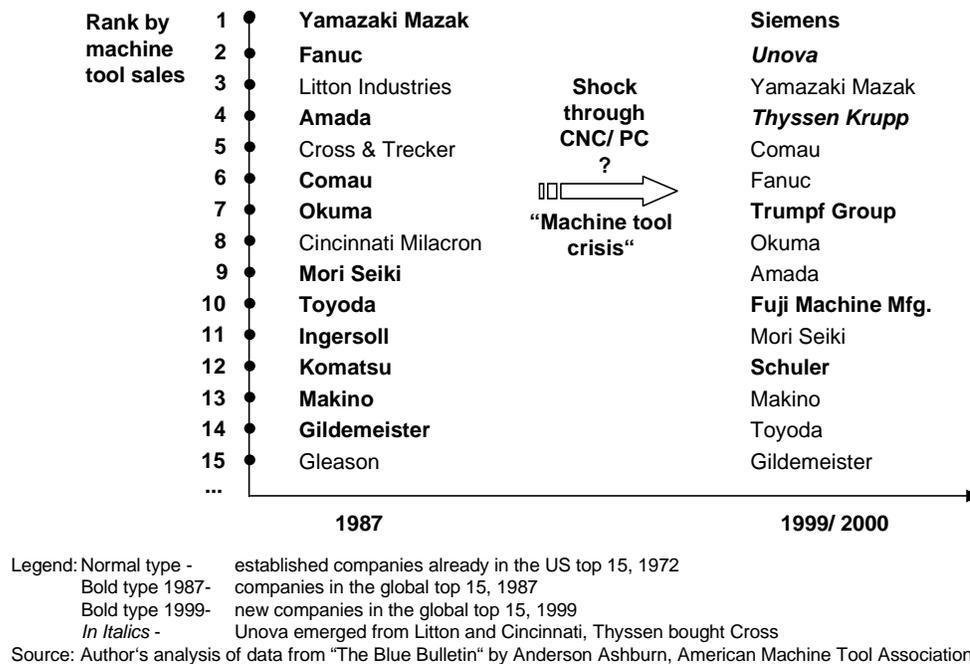
Data of worldwide competition at the single company level is available since the late 1980s¹⁸. It indicates that the subsequent phase of technological change, the implementation of PC technology, equally led to changes in the market. After an additional time frame of twelve years, none of the in 1971 originally leading companies remained in the top 15 (see figure below). Two of the newly leading companies in 1999/ 2000, UNOVA and Thyssen

¹⁷ These effects are described in Rendeiro, "How the Japanese Came to Dominate the Machine Tool Business."

¹⁸ Ashburn, "Blue Bulletin."

Krupp, emerged from takeovers of several of the top-ranking companies in 1971. UNOVA is, as a corporate investor, owner of two of the former top companies, Litton Industries, and Cincinnati Milacron. The German Thyssen Krupp took over Cross&Trecker, Giddings&Lewis, and several other international companies, in particular in Germany¹⁹.

Global Machine Tool Industry: Market development after CNC and during PC introduction



At first sight, the events within the industry might also seem to be the result of consolidation through mergers and takeovers. However, the total number of companies rather increased over the last 50 years²⁰. The small-scale structure of the industry, which might be an indicator of market maturity²¹, remained rather unchanged from the 1970s²² until now - the distribution of size of companies has remained the same since 1955. In Germany some 40% were companies with less than 50 employees. At no time more than

¹⁹ E.g. Witzig&Frank, Hüller Hille, etc.

²⁰ With established companies in the US and Europe disappearing, and new companies entering in Japan.

²¹ Level of concentration expresses degree of maturity in markets. See for example Steven Klepper, "Entry, Exit, Growth, and Innovation over the Product Life Cycle," American Economic Review 86, no. 3 (1996): 562-583.

5% of the companies had more than 1000 employees²³. In fact, scale effects on the production side²⁴ seem to be rather weak. The variety of machines offered until today is surprisingly large, almost no two machines seem to be identical. Each producer adds its own “flair”, and defines its own market niches²⁵. The fact that many small companies operate in the machine tool market led to a phenomenon which is typical for this industry - the disproportion in mere size of machine tool companies and customers. Consolidation in the automotive industry (as well as in the electronics industry) in the last 20 years puts machine tool producers in a position of low bargaining power. Especially when supplier and customer are one and the same big industrial giant (as with Siemens), the small companies are in a particular weak position²⁶.

These special aspects of the machine tool industry and the events in the market accompanying and following technological change suggest that it is fruitful to investigate the effect of the introduction of numerical control (NC) more closely.

B. The Survey

A new generation of decision-makers moves into position in the machine tool industry. Most of the managers who witnessed the fundamental change of technology are retired or about to retire shortly. Unfortunately until now only few strategic oriented studies have been conducted systematically within this industry²⁷. Researchers with a business interest prefer to study industries with shorter reinvestment cycles. Results in such

²² Thomas G. Marx, "Technological Change in the Structure of the Machine Tool Industry," MSU Business Topics 27, no. 1 (1979): 41-47.

²³ P. 9 of Gerhard Schwab, "Die Entwicklung der deutschen Werkzeugmaschinenindustrie von 1945 - 1995," (Frankfurt am Main: Verein Deutscher Werkzeugmaschinenfabriken e.V., 1996), 1 - 62. P. 38 of VDW, "The German Machine Tool Industry in 1999," (Frankfurt: Verein Deutscher Werkzeugmaschinenfabriken e.V., 1999), 1 - 52.

²⁴ On the finance side, size had indeed a positive effect on company survival. Especially in a hugely cyclical business with order volumes that are at times 10% of the annual turnover, a strong credit line is necessary. Also implementing the new NC technology meant a huge financial investment. Mr. Willi Gauch, Industry-Expert-Interview-Series, "Interview Series."

²⁵ Colleen A. DeJong, "All Machine Tools are not Created Equal," Automotive Manufacturing & Production 110, no. 3 (1998): 78 - 81.

²⁶ E.g. when the terms of payment are not being followed. Mr. Cuatto, Giana, and Mr. Passemard, Industry-Expert-Interview-Series, "Interview Series."

industries take place quicker and time series observations do not have to include periods longer than a decade. The computer industry and its related industries with their less than half-decade cycles are often termed the “fruit-flies”²⁸ of business research.

Not so the machine tool industry. The effect of NCs increased from the 1950s to this day. To be able to use primary sources and avoid the experiences, which were made by the past generation of managers being lost, a present day survey in the machine tool industry had to be conducted. The research in this paper is based on qualitative interviews conducted in person or over the telephone with over one hundred industry experts and decision-makers with the emphasis on motivating them to participate in a data collection based on structured questionnaires. To identify potential expert candidates, we reconstructed a list of about 280 companies that were established in 1970 – a time at the beginning of the development of NC/ CNC technology. Sources were historic consultants’ reports²⁹, company rankings of industrial associations³⁰, trades show catalogues³¹, historic engineering school literature from the archives of the Rice University Library, Houston, Texas³², engineering and engineering management journals, and company anniversary publications³³. 59 companies were finally willing to send data to identify the correlation of business success and potential influential factors in the face of radical technological change. The selected companies are from nine countries (Japan, Germany, Italy, Switzerland, Taiwan, United States, United Kingdom, France and Spain), covering the top

²⁷ This view is supported by Roberto Mazzoleni, "Learning and Path-Dependence in the Diffusion of Innovations: Comparative Evidence on Numerically Controlled Machine Tools," *Research Policy* 26, no. 4,5 (1997): 405 - 428.

²⁸ Clayton M. Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms To Fail*, 1 ed., The management of innovation and change series (Boston: Harvard Business School Press, 1997).

²⁹ Mainly from UBM/ Mercer Management Consulting, Boston Consulting Group

³⁰ See list of members of VDW and WS Atkins Management Consultants in assoc. with Ifo-Institut VDW, "Strategic Study on EC Machine Tool Sector," (VDW), 43. Also Ashburn, "Blue Bulletin."

³¹ Like EMO, EMO Hannover - *The World of Machine Tools - Catalogue*, vol. 14 (Hannover: Generalkommissariat der 14. EMO Hannover, Messengelände, 2001). Also the 1997 edition and older ones.

³² Several historic exemplars were screened for pictures of machines with the names of producers on them. Like in Charles R. Hine, *Machine Tools for Engineers*, 2 ed. (New York, Toronto, London: McGraw-Hill Book Company, Inc., 1959).

³³ Like Yasunori Kuba, *Meister der Fertigungstechnologie - Die 70jährige Geschichte von Mazak* (Taito-ku, Tokyo: Yamazaki Mazak Corp., 1989). And Fritz R. Glunk, *100 Jahre Pittler 1889 - 1989*, ed. Prof. Dr. Dieter Weidemann - Vorsitzender des Vorstandes der Pittler Maschinenfabrik AG (Langen: Britting Verlag, 1989).

nine machine tool exporting countries in 1999³⁴. Decision-makers that worked for the largest machine tool manufacturers in the former German Democratic Republic (GDR) were also interviewed. The companies were all established in the 1960s before the introduction of NCs upset the industry. It is crucial for this study that the sources are global. What might seem valid on a national scale is not necessarily true when events in other countries are taken into consideration³⁵.

Comments, which were made in the questionnaires, were also included. In addition, statements from industry experts in academia, industry associations, and management consulting companies are contained in this survey.

This contribution builds on the already widely existing literature. It aims at filling in gaps and perspectives which have not yet been covered in publications till today as well as cross-checking the various sources. The primary objective is to describe the process of the innovation of digital control in the machine tool industry and to confirm the disruptive nature of this new technology. The article briefly outlines how categories and core elements of machine tools evolved and how this evolution influenced the industry structure. It summarizes the history of invention of NCs, discusses the spread of the technology in three major waves and elaborates on the extent to which NCs have influenced competition within the industry. A separate section explores the potential effect of other external factors during the 50-year period as well as the remarkable success story of Japan.

³⁴ Pp. 32, 33 of VDW, "The German Machine Tool Industry in 1999," (Frankfurt am Main: Verein Deutscher Werkzeugmaschinenfabriken e.V. (VDW), 1999).

Number 10 is South Korea. The list of the top 10 producers includes the same countries, except Korea. China would be at rank 6 of this list. For top 10 consumers, Switzerland drops out and Brazil is at rank 7. The same countries are also the top 10 importers.

³⁵ For example the effects of the oil crises of the 70s left their effect on the spread of technology in the US industry, not at all, though, on the Japanese industry. The same is true for the number of firms - what might look like a decrease of a number of companies from a German perspective, is not true on a global scale, as quite a few companies in Spain, Taiwan, Japan entered the market at different periods of time. A typical essay from a German perspective is Schwab, "Die Entwicklung der deutschen Werkzeugmaschinenindustrie von 1945 - 1995." On effects of concentration in Germany see Manfred Fleischer, *The Inefficiency Trap: Strategy Failure in the German Machine Tool Industry*, ed. Edition Sigma (Berlin: Wissenschaftszentrum Berlin für Sozialforschung - WZB, 1997).

C. Categories and components of machine tools and their influence on the industry structure

Machine tools are split up by production process into chip-making and forming machines. The most important making or cutting processes are turning, drilling, boring, milling, and grinding. Important metal forming processes are forging, pressing, bending, and shearing³⁶. To date most national statistics follow these categories³⁷. Producers' machine portfolios traditionally focus on a single process technology. Before the advent of numerical control technology some producers specialized in turning machines, others in grinding machines, presses, etc. The introduction of numerical controls allowed the combination of several cutting processes into machines with higher flexibility. Likewise most companies increased their knowledge of cutting production technologies. Nevertheless there are until today – with the exception of some large Japanese corporations - only few examples of machine tool producers that manufacture both cutting and forming machine tools.

The disruptive effect of the new technology, which we selected, is most visible in chip-making machine tools³⁸. This is why we will focus on this group of machine tools when it comes to discussing the technical aspect. The main components of chip-making machine tools are frames, leadways and bearings, drives, and controls³⁹. **Frames** carry mountings for workpieces and tools and support all moving mechanical elements. There are high demands on the rigidity of frames. Undesirable vibrations of the frame result in diminished accuracy in the workpiece.

Producing accurate **leadways and bearings** has been considered an art in the industry of investment goods. Before electronic controls and advanced measurement systems could react “real time” on feedback from in-process measuring, only very carefully manufactured bearings guaranteed a highly accurate movement of the main spindle, the main spindle

³⁶ An online reference and explanation of how machine tools work can be found at <http://encarta.msn.com/find/Concise.asp?z=1&pg=2&ti=761554377>

³⁷ As for example in VDW, "The German Machine Tool Industry in 1999."

³⁸ Dr. Renn, Müller-Weingarten AG, Industry-Expert-Interview-Series, "Interview Series."

³⁹ Heinz Tschätsch and Werner Charchut, *Werkzeugmaschinen: Einführung in die Fertigungsmaschinen der spanlosen und spanenden Formgebung*, 6 ed., *Das Fachwissen der Technik* (München, Wien: Carl Hanser Verlag, 1991).

driving the tools being the most important mobile part of the machine tool. The accuracy of the workpiece mainly depends on the repetition and positioning accuracy of the spindle with differing numbers of revolutions, drive torques, and cut forces. Equally the accuracy of leadways for other mobile parts (e.g. the table onto which the work piece is mounted) and the quality of mechanical controls influences the precision of the workpiece. Notably Swiss companies, historically closely connected to the watch industry, worked at a high level of precision engineering⁴⁰. The know-how to produce highly precise systems⁴¹, which consists of very accurate leadways, bearings and mechanically controlled drives, was an important competitive advantage acquired over generations, leading to the establishment of a large industrial base for investment goods in Switzerland⁴².

Drives consist of electric motors and gears which control the number of revolutions between motor and tool and in addition convert the uniform movement of the motor into a straight, curved, turning or other movement. The main drive is responsible for generating the movements for cutting; additional drives generate thrust and the movements for positioning or shifting gears. Several innovations in particular in electric motors (e.g. step motors, linear motors) have helped to improve drives. The effects of innovations in gear technology were not radical enough to have any effect on the business success of manufacturers of machine tools. Motors were traditionally purchased from suppliers so that the competence⁴³ of machine tool producers was not deeply affected. Equally, the changes did not have such a radical effect on the whole machine architecture⁴⁴; they were rather

⁴⁰ Schneeberger Linear Technologies, Roggwil, and Güdel AG, Langenthal, Switzerland, specialized on linear leadways, are examples of companies which traditionally excel in precision engineering. Their customers are in the machine tool industry but also in the electronics and semiconductor industry, in medical and biotech industries - <http://www.schneeberger.com/> and <http://www.gudel.com/>

⁴¹ The system of these single components has to be highly accurate in combination. I.e. it is not sufficient to produce highly precise components – they also need very careful mechanical integration. See p. 264 of Günter Spur, *Die Genauigkeit von Maschinen: eine Konstruktionslehre*, 1 ed. (München, Wien: Carl Hanser Verlag, 1996).

⁴² According to VDW 06/2000 statistics, Switzerland is still number 5 in machine tool production worldwide, after Japan, Germany, USA, and Italy.

⁴³ Skills and knowledge as key assets for competitive advantage is discussed in Michael L. Tushman and Philip Anderson, "Technological Discontinuities and Organizational Environments," *Administrative Science Quarterly* 31, no. 3 (1986): 439-465.

⁴⁴ The extent to which a new technology influences a product's architecture has a significant effect on a company's success or failure. See Rebecca M. Henderson and Kim B. Clark, "Architectural Innovation: The

modular in character and did not change the product's value proposition⁴⁵. Therefore innovations of drives did not visibly affect the machine tool companies.

The most fundamental changes occurred with the **controls**. Controls switch the drives on and off, they activate the gears and clamps, and direct the movement of the tools. According to which technique they use, controls are classified into mechanical, in some cases into hydraulic and pneumatic, and lastly into electric controls, the latter nowadays usually being based on digital logic. This technology managed to upset the whole industry⁴⁶.

D. Numerical control technology

The conventional method of machine tool operation for small lot production (as in contrast to mass production) used mechanical arrangements of bars and cams, as well as sequencing and cycle timers to control the tools of the machines in the production of particular shapes. Fixtures, jigs, and templates, which were often expensive, were used to keep the work in place and to guide the tools⁴⁷. For example the manufacturing of helicopter blades required about fifty templates. The machine tool producers themselves manufactured mechanical as well as hydraulic and pneumatic controls.

Digital or numerical⁴⁸ controls direct machine tools automatically through a programmed sequence of operations (drilling, milling, boring, etc.) with the aid of computerized control tapes. Machine feed and speed, distance and direction, flow of

Reconfiguration of Existing Product Technologies and the Failure of Established Firms," *Administrative Science Quarterly* 35, no. 1 (1990): 9-30.

⁴⁵ For a discussion of different dimensions of categorizing technological change and measuring its effect on companies' survival see Heinrich M. Arnold, "Can great companies survive technology shocks? - A literature overview," Munich School of Management, Electronic Working Paper Series, no. 1/2001 (2001).

⁴⁶ A large part of the above information can be found on pp. 58-122 Tschätsch and Charchut, *Werkzeugmaschinen: Einführung in die Fertigungsmaschinen der spanlosen und spanenden Formgebung*.

⁴⁷ For a detailed description of how numerical controls work see p. 137 in Horst Witte, *Werkzeugmaschinen: Grundlagen und Prinzipien in Aufbau, Funktion, Antrieb und Steuerung spangebender Werkzeugmaschinen*, 7 ed., Kamprath-Reihe (Würzburg: Vogel Buchverlag, 1991).

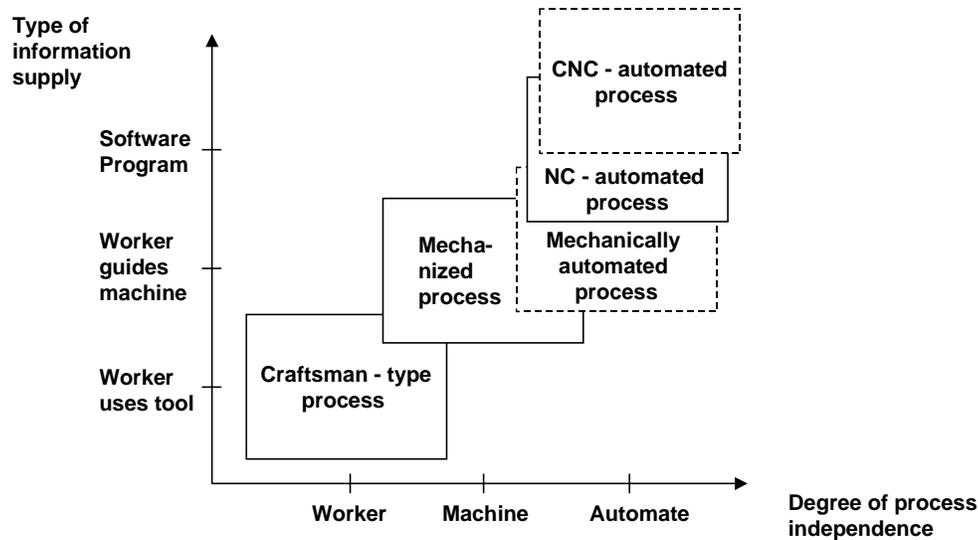
⁴⁸ The term numerical stems back to the early years of the development project of digital controls at the MIT together with the Parsons Corporation.

coolant as well as selection of tools is performed automatically. The change of instructions happens easily by replacing the control tape with another program⁴⁹.

Numerical controls marked major changes in the way automatically controlled processes had traditionally been carried out. The new technology was a further step in how information about the workpiece was supplied to the machine. Originally the worker guided the process while he was working with the tools or controlling the process and being present at the machine. In some areas of application, mechanical controls could provide a considerable degree of automation. In particular Swiss screw-type machines were independent of the operator during the production run. The range of shapes was clearly limited but this type of machine was a milestone in the development of an automated process. Digital control technology introduced this level of independence for a larger number of different chip-making machines. NC controls were programmable so the worker did not have to be present during the production process. An automated system for complex parts became possible – the “automate” (see picture below). Technically this meant the ability to execute real-time control through the use of digital signals corresponding to numbers in contrast to the traditional way of using continuous signals that were analogs of physical quantities.

⁴⁹ The description of functionality follows closely Marx, "Technological Change in the Structure of the Machine Tool Industry."

 Development Stages of Production Processes



Source: Own improved depiction, based on depiction p. 324 of Günter Spur, "Die Genauigkeit von Maschinen", München, Wien, Carl Hanser Verlag 1996

This change can be compared to the substitution of direct current power by alternating electric power, the emergence of the automobile as a means of transportation at the end of the 19th century or the displacement of vacuum tubes by transistors in the 1960s⁵⁰.

In the development of numerical controls there have been minor discontinuities⁵¹. The early numerical controls were "hardwired" and specifically constructed for the various types of machine tools. These first controls lacked flexibility, were expensive and prone to failure. In the early 1970s the numerical control unit was then based on a minicomputer. A Swedish firm initially introduced it. However Japanese firms picked up the computer-based control technology with more momentum and systematically developed it further⁵². In 1974

⁵⁰ See p. 166 of Reintjes, Numerical Control: Making a New Technology.

⁵¹ Ellinor Ehrnberg and Staffan Jacobsson, "Indicators of Discontinuous Technological Change: An Exploratory Study of two Discontinuities in the Machine Tool Industry," R & D Management 27, no. 2 (1997): 107-126.

⁵² Kong Rae Lee, "The role of user firms in the innovation of machine tools: The Japanese case," Research Policy 25 (1996): 491-507.

microcomputers were used to make the controls programmable – the computer numerical controls (CNC). This allowed the use of the same control hardware for a number of machine tool types. Now “merely” the software had to be modified. With quantities growing, the price for numerical controls dropped and quality stabilized. Implementation of the numerical control technology became simpler for producers and users of machine tools, programming became easier, further automation⁵³ feasible.

The price/ performance ratio greatly improved and eventually opened up a mass market for numerically controlled machine tools.

Typical for the history of NCs, the initial idea for numerical control was conceived at Parsons Corporation, one of the then leading manufacturers of mechanical parts - the development occurred beyond the scope of the machine tool companies.

E. Location of invention, role of national research programs, and no advantage for first movers

E. 1. The first years of the new technology

The modern development of NCs started about 1948 - 1949. A relevant stakeholder in this development was the United States Air Force, which desired to have machines for the aircraft industries that were able to manufacture complex parts cheaper, faster and more accurately than by conventional methods. So the Air Force financed proof-of-feasibility studies of machine tools which could perform automated contour cutting. Under the leadership of John Parsons Company and the Servomechanisms Laboratory of MIT, the first experimental models of milling machines were developed and by 1951 tested in a few plants.

John T. Parsons, vice president of the Parsons Corporation, Aircraft Division, in Traverse City, Michigan City, conceived the initial idea of “data systems” for machines. In spring 1949, he contacted Professor Gordon S. Brown of MIT’s Servomechanisms Laboratory⁵⁴. The Servomechanisms Laboratory⁵⁵ had done research on digital feedback

⁵³E.g. for tool changing, material handling, and supervising the production process.

⁵⁴ A detailed account of the research project at MIT and the collaboration between MIT, the US Air Force, the Parsons Corporation from MIT’s perspective is given by one of the project managers in his book Reintjes, *Numerical Control: Making a New Technology*. Much of the information summarized here is taken from this

control for military applications (control of gun turrets, etc.) during the war and was looking for industrial applications of their know-how. Through previous research⁵⁶ the Servomechanisms Laboratory had been sensitized for potential application in machine tools. Parsons could convince the Air Force to finance a proof-of-feasibility study. He envisioned the development of the “Cardamatic Milling Machines I and II” in a joint effort by MIT and Parsons Corporation. The Parsons Corporation thereupon received 200.000 US\$⁵⁷ from the Air Force divided up into four phases, of which 80.000 US\$ were used for research at the Servomechanism Laboratory. MIT itself spent a total of 360.000 US\$ on the development. The remaining 280.000 US\$ were billed directly to the Air Force. As basis for the experimental machine a conventional commercial three-axis milling machine from the producer Cincinnati Milling Machine Company was used. September 1952 the experimental machines were demonstrated publicly.

After having sponsored the development of an experimental NC machine tool, the Air Force hoped that the industry would pick up the new technology. Colonel Wilbur R. Carter, the then head of the Manufacturing Methods Branch of the Air Materiel Command, urged the machine tool builders to turn the new technology into marketable products. The industry’s reaction was far from being enthusiastic. MIT and the Air Force even initiated a program for “information-dissemination” of NC technology in the years 1953 to 1954.

E. 2. Machine tool manufacturers get involved – what happened to the pioneers

Giddings&Lewis Machine Tool Company, Fond du Lac, Wisconsin (G&L) was one of the few exceptions that tried to improve the tolerance of its milling machines through numerical controls. The concerns about the complexity of the director unit (a more simpler

book. Another summary of the first years, which is deviating in some points is given in Mazzoleni, "Learning and Path-Dependence in the Diffusion of Innovations: Comparative Evidence on Numerically Controlled Machine Tools."

⁵⁵ The Servomechanisms Laboratory was established in the late 30s and changed its name in 1959 to Electronic Systems Laboratory to account for a broadened scope.

⁵⁶ A PhD thesis „Analysis and Design of Sampled Data Systems“ by William K. Linvill resulted out of a computer project at the MIT Department of Electrical Engineering, called „Whirlwind“.

⁵⁷ This amount turned out to be insufficient and was more than doubled in the course of the project. At this time the annual salary of an engineer was about 5000 US\$.

processor unit) led to another research project together with MIT⁵⁸ and General Electric. Enriched by staff members from the Servo Lab, Giddings&Lewis spun off a subsidiary, Concord Control Inc., Brighton, Massachusetts, to produce digital directors. Parallel to the National Machine Tool Builders Association Show in 1955 the first commercial model of a five-axis NC milling machine went on display⁵⁹ at the Giddings&Lewis facilities⁶⁰.

Cincinnati Milling chose to establish a relationship with the British company EMI (Electrical and Musical Instruments) for the manufacture of control systems. The cooperation failed and Cincinnati began to produce control units of its own.

In 1956 Kearney&Trecker manufactured one of the first commercial NC milling machines in the US⁶¹, an incident that they still use proudly in their marketing material. The most famous name of one of these early models was "Milwaukeeematic". The company cooperated with Bendix, Detroit, as its supplier of electronic equipment and supplied products to the Aircraft Manufacturer Northrop Company. Bendix' Research Division had begun work on numerical control systems in the early 1950s led by one of the Servo Lab's alumni. Kearney&Trecker as well as Giddings&Lewis⁶² were later taken over by the German group Thyssen Production Systems.

One of Kearney&Trecker's first customers was Hughes Aircraft Company, Los Angeles. At that time Hughes Aircraft Company employed about 30,000 workers and had divisions for electronics, aerospace, and defense. The visionary Howard Hughes led the company. Born to a upper class family in Texas, he owned the movie company 20th Century Fox as well as the airline TWA. Around 1957, Hughes Company decided to develop a new product, a numerical control unit, and to market it together with a machine

⁵⁸ The program's research supervisor was J. Francis Reintjes who documented the research activities at MIT in his book Reintjes, Numerical Control: Making a New Technology.

⁵⁹ Much of the information in this paragraph was taken from Anthony A. Romeo, "Interindustry and Interfirm Differences in the Rate of Diffusion of an Innovation," *The Review of Economics and Statistics* 57, no. 3 (1975): 311-319.

⁶⁰ The development team did not finish the machines in time, so G&L flew in interested parties from the exhibition.

⁶¹ Ernst Raiser, Ex-Burkhardt&Weber, Dzems Bruvelis, UBM, Industry-Expert-Interview-Series, "Interview Series."

⁶² Giddings&Lewis went public in 1982, bought by the American company EMCO in the late 1980s, and finally taken over by the group Thyssen Production System in 1997.

tool.⁶³ Hughes had bought the first NC machine from Kearney& Trecker but decided to exploit the favorable exchange rate of the US Dollar abroad. With an exchange rate of 1 US\$: 4.20 Deutschmarks and a relatively low interest in digital control technology by the US machine tool industry, it is not surprising, although less known, that the mechanical side of one of the first⁶⁴ commercial machining center was developed and produced by a German manufacturer “Burkhardt&Weber” in Reutlingen, Germany. Hughes Tool Company provided control units – which then consisted of radio tubes – as well as all other electric and hydraulic parts. Burkhardt&Weber designed and manufactured the machines. According to the agreement between the partners sales responsibility was given to Burkhardt&Weber for Western Europe, with the exception of Sweden, and to Hughes for the rest of the world. The NC machine series were named MT3 and MT3 A. These machines were based on classical drilling machines onto which the NC module was mounted. At the Hannover Exhibition in 1960, the machining center was presented to the public and attracted great attention but also great confusion, as the area of application for such machines was not clear to the visitors. Although Burkhardt&Weber took the technology seriously – they established an organizational unit for NC machines, which was about 30% the size of the total company - Burkhardt&Weber did not benefit from first mover advantages. It was not until 1965 that the first MT3 A could be sold (to the French company Snecma, Paris). In the US, about 150 machines were sold by the mid-1970s. In 1966 Burkhardt&Weber started its own development program for a machining center, the MC 4, and developed a rather new concept for it. In the case of Burkhardt&Weber, NC technology did not lead to any considerable sales growth or share in the market. The company never grew out of its sub-critical size to finance its larger projects (some of them were up to 25% of the company’s annual turnover of about 200 million Deutschmarks). In 1982, the company was bought by the Swiss technology corporation Georg Fischer that

⁶³ Ernst Raiser, *Wie das erste numerisch gesteuerte Bearbeitungszentrum bei Burkhardt+Weber entstand* (1) [Compact Disk] (Burkhardt+Weber Gruppe, 2001 [cited]).

⁶⁴ Some of the interview partners claimed that it was the first one.

sold it off again in 1994. In 1992 and 2001, Burkhardt&Weber filed for bankruptcy and was recently taken over by the shareholders of the Italian corporation Riello⁶⁵.

As the value of the new technology and the potential competitive advantage it entailed were not fully appreciated in the US, the Japanese company Yamazaki was able to acquire the US license for the MT3 A from Hughes Aircraft. At first Yamazaki Mazak wanted to cooperate with Burkhardt&Weber but after the failure of such a cooperation it used the license to study NC machines⁶⁶. Originally Yamazaki had only built conventional lathes. In February 1966 the technical team of Yamazaki started to investigate new technology, in particular NCs. They used the license to build one MT3 A machine and study the technology of machining centers. In the fall of 1968, Yamazaki was able to present its own series of NC machines - the turning centers 800R, 1000M, and 1500R, and the machining center BTC5.⁶⁷ The access to NC technology was the basis for the company's later success, which became the market leader in machining centers, Yamazaki Mazak.

In Germany, Schiess AG⁶⁸ presented the first heavy milling and boring machine in 1957 using a Brown, Boverie and Cie. controller⁶⁹. The company merged with Dörries charmann in 1992 and went bankrupt in 1994, the same year its parent company, Bremer Vulkan, also went bankrupt. In 1959 Pittler AG produced the first German NC – lathe⁷⁰.

The years between 1959 and 1965 were a time of rapid expansion for numerical controls. In 1958 the first multifunction, multipurpose machining center was introduced⁷¹.

⁶⁵ Dr. Hans Klein, Ernst Raiser, and Wilhelm Gauch, Ex-Burkhardt&Weber, Industry-Expert-Interview-Series, "Interview Series."

⁶⁶ Dr. Hans Klein, Ex-Burkhardt&Weber, Ibid.

⁶⁷ Kuba, Meister der Fertigungstechnologie - Die 70jährige Geschichte von Mazak.

⁶⁸ Dr. Reinhard Fleck, Ex-Schiess, Industry-Expert-Interview-Series, "Interview Series."

⁶⁹ See p. 199 Fleischer, *The Inefficiency Trap: Strategy Failure in the German Machine Tool Industry*.

⁷⁰ Schwab, "Die Entwicklung der deutschen Werkzeugmaschinenindustrie von 1945 - 1995.", Glunk, 100 Jahre Pittler 1889 - 1989. At the Hanover exhibition 1960, 14 German companies showed NC machine tools. Among them Berliner Maschinenbau AG, Burkhardt&Weber, Bohle, Collet&Engelhard, Droop&Rein, F. Werner, Heller, H. Kolb, Hüller, Pittler, Scharmann, and Waldrich. Regarding which machine type these companies presented, the overview on pp. 530/531 in Spur, Vom Wandel der industriellen Welt durch Werkzeugmaschinen. is inconsistent with other sources like Schwab and Glunk, also with p. 200 in Fleischer, *The Inefficiency Trap: Strategy Failure in the German Machine Tool Industry*. The interview series with industry experts named Collet&Engelhard, Pittler among others as producers of lathes around that time. The overview in Spur categorizes them as producers of boring mills.

⁷¹ Rendeiro, "How the Japanese Came to Dominate the Machine Tool Business."

At the 1960 IMTE show in Chicago there were already 90 different models of NC machines being presented.

E. 3. National programs to develop a new technology

With the development of automated machines the need for a new generation of sensors emerged that could express measured velocities and positions in digital form. At the same time a market was created for a digital computer which could be integrated into sensors, controllers, and machine tools, and which could manage the real-time digital control of the entire system. There was an opportunity for breakthrough in the concept of programming. The idea was to create hierarchical structured computer languages in which commands could be expressed in simple English-sounding words rather than cryptic, codified form, and which would also be able to automatically compile subprograms into an integrated systems program. “The need propelled the research” as one of the MIT program managers, Dr. Reintjes, put it⁷².

Most of the industrialized countries started national programs to meet these needs and to accelerate and intensify the development and introduction of NCs.

In Germany five universities – Berlin (Prof. Spur), Stuttgart (Prof. Ehrhardt, Prof. Stute), Aachen (Prof. Opitz), Karlsruhe (Prof. Warnecke) and Hannover (Prof. Kienzle, Prof. Osenberg) cooperated closely with industry and industrial organizations. These universities provided specialized knowledge on individual manufacturing functions such as turning, milling, forming, computer control, and computer design⁷³. As a result several direct numerical control systems were developed, most notably a national manufacturing software system called “EXAPT”, which is still being promoted by the “EXAPT-Verein” in Aachen. These institutions also trained management resources for the industry. Many industry experts who participated in this study as well as contributors to the survey can be

⁷² P. 166 in Reintjes, *Numerical Control: Making a New Technology*.

⁷³ Taiwan imitates the approach of university – industry cooperation for R&D in the recent years. Shiu Hsu and Pao-Long Chang, "Promoting Technological Capabilities of Small and Medium-Sized Enterprises through Industry-University Cooperation: Case Study of Taiwan Machine Tool Industry," *International Journal of Manufacturing Technology and Management* 1, no. 2,3 (2000): 257 - 270.

found in the Aachen alumni register⁷⁴. Many industrial organizations, notably the “Verein Deutscher Werkzeugmaschinenfabriken e.V.” (VDW) helped identify market needs and tried to initiate cooperations and research projects. The effort to start horizontal cooperations was largely unsuccessful as most of the companies preferred to conduct their business stand-alone, however several consulting reports delivered insight into the state of the art and competitive environment. It was, however, different for vertical cooperations, traditionally of importance in Germany⁷⁵. Companies cooperated strongly either with their customers or, even more often, with their supplier of numerical control units, namely Siemens. Siemens began developing numerical control units in 1958 and was able to deliver the first units two years later⁷⁶. The electronics company helped to bring the German machine tool industry up to speed and organized trainings for machine tool companies.

Similar steps were taken in Norway, where four of the country’s leading firms cooperated with the technical University of Norway, the Central Institute of Industrial Research, in order to develop a national manufacturing software system.

France’s association of the fifty largest manufacturers assisted in the acquisition of high-tech equipment, management and technical information and education for managers.

In the Netherlands university research focused on the development of software for the automation of the production process.

In the United Kingdom, the efforts of the Production Engineering Research Association, universities, and industry groups focused on cellular manufacturing in order to reduce production time. The industry, though, was technologically rather “backward”⁷⁷ and

⁷⁴ Walter Eversheim et al., *Anschriften der Freunde und ehemaligen Mitarbeiter des Laboratoriums für Werkzeugmaschinen und Betriebslehre der Rheinisch-Westfälischen Technischen Hochschule Aachen*, ed. Herwart-Opitz-Haus Laboratorium für Werkzeugmaschinen und Betriebslehre der Rheinisch-Westfälischen Technischen Hochschule Aachen (Aachen: 1980).

⁷⁵ See the discussion of results from the “Mannheim Innovation Panel” in Najib Harabi, “Innovation through vertical relations between firms, suppliers and customers: A study of German firms,” *Industry and Innovation* 5, no. 2 (1998): 157 - 172.

⁷⁶ Schwab, “Die Entwicklung der deutschen Werkzeugmaschinenindustrie von 1945 - 1995.”

⁷⁷ Anne Daly and Daniel T. Jones, “The Machine Tool Industry in Britain, Germany, and the United States,” *National Institute Economic Review*, no. 92 (1980): 53.

too slow in picking up CNC technology as a comparison with the Swiss industry showed⁷⁸. The Swiss industry invested substantially in R&D to innovate their product performance. Through a timely adoption of new technologies they were able to remain in a leading position in the world markets, whereas the UK industry, with a few exceptions⁷⁹ (mostly the “600 group”), almost disappeared.

However, primarily Japan, which will be described in a separate section below, and Germany developed the ability to create complete automated systems.

As the US companies dropped further behind and after more than 200 companies had dropped out of the market by 1984, the necessity to spur research and development efforts was felt. Measured as a percentage of the GNP (gross national product), Japan and Germany both spent more in private research and development than did the US⁸⁰. Leading manufacturers like Cincinnati Milacron increased their R&D budgets, several industry groups were forming joint research ventures, the automotive industry, as the most important client industry, the Department of Defense, and individual states providing financial backing⁸¹.

F. Patterns and extent of technological change: between shock and evolution

Over the course of fifty years three major technological innovations had a major effect on the machine tool industry. Three waves, lasting about ten years each, can be observed during which the new technologies experienced strong diffusion and were implemented in the factories of the manufacturing industry.

⁷⁸ Charbel Ackermann and Jeffrey Harrop, "The Management of Technological Innovation in the Machine Tool Industry: a Cross-national regional survey of Britain and Switzerland," *R&D Management* 15, no. 3 (1985): 207 - 218.

⁷⁹ Dr. Stephen LeBeau, 600 Group, Industry-Expert-Interview-Series, "Interview Series."

⁸⁰ Anonymous, "Bring Technology Out of the Lab and Into Your Plant," *Production* 86, no. 2 (1980): 83.

⁸¹ Cincinnati Milacron increased its R&D budget from 1983 to 1984 by 19% to 36 million US\$. General Motors orders research on advanced manufacturing research, and the government spent about 37 million US\$. Harlow Unger, "Industrial America: Strategies for Recovery in Machine Tool Industry," *Industrial Management* 9, no. 4 (1985): 13. Forrant describes some of the events from a US perspective in Robert Forrant, "Good jobs and the Cutting Edge: The U.S. Machine Tool Industry and Sustainable Prosperity," Working Paper - University of Massachusetts Lowell, no. 199 (1997): 1 - 30.

The extent to which the new technologies appeared as a major disruption or a shock to the industry can be expressed in three categories⁸². The first category is a fundamental change in product architecture. Numerical controls did not only mean the innovation of one component, it meant the complete redesign of the whole machine and its implementation into an automated production system. Several machine tool groups, each representing one specific function, converged into multi-purpose machines.

The second category was a disruption in competence, which gives companies competitive advantage. The competence to manufacture highly accurate mechanics made way for the need to develop electrical engineering know-how. Numerical controls enabled most manufacturers to produce accurate machines. A change in the value chain occurred; numerical controls were mostly purchased from electronics companies.

The third category is that of value proposition. Numerical controls reduced the value of the image, which established companies had built around themselves for decades, i.e. that they would be exclusive producers of machines with high accuracy. Now almost every manufacturer could increase the accuracy of his machines with the help of NC. The criteria for the purchase of a machine tool became different. Price was among one of the most important ones. It indicates a change of how the products were valued.

F. 1. Three waves of technological innovation

Seen from the position of today the development and implementation of the new technology happened in several waves. To many contemporary decision-makers the change in technology and its effects on the companies' success appeared⁸³ to be positive. Long reinvestment cycles of 10-20 years⁸⁴ in the manufacturing industry were taken as given

⁸² The usefulness of these three categories to discuss "technology shocks" is being presented in Arnold, "Can great companies survive technology shocks? - A literature overview." Another, although less practical, framework to monitor innovation is proposed in Daniele Archibugi and Roberto Simonetti, "Objects and Subjects in Technological Interdependence. Towards a framework to monitor innovation," *International Journal of the Economics of Business* 5, no. 3 (1998): 295 - 309.

⁸³ Dr. Klein doubts a disruptive effect of this technological change. He observed a fundamental, although rather incremental, change in the industry. Industry-Expert-Interview-Series, "Interview Series."

⁸⁴ "Long waves" of about 10 - 20 years on the company level can be observed in the sales data on pp. 11, 12 collected in Rainer Klump and Beate Männel, "'Lange Wellen' der Unternehmenskonjunktur," *Zeitschrift für Unternehmensgeschichte* 40, no. 1 (1995): 1 - 34. Here the conclusion is also drawn for the manufacturing industry in general.

because machine tools last a long time. With appropriate service, maintenance, and occasional reconditioning they can perform for many years. Between 1925 and 1950 about 50% of the machine tools used in the US were 10 and more years old. Roughly 15% were older than 20 years⁸⁵. With these rather long reinvestment cycles, even drastic technological disruptions become leveled out at first sight over the years⁸⁶. But when longer periods are considered, a wave pattern can be seen of how the different NC technologies affected the industry.

The **first wave** obviously was the introduction of numerical controls for machine tools in the 1950s and 1960s. From 1959 to 1965 the number of shipments increased over a seven year period by 40% on average⁸⁷, i.e. from about 200 to about 2050, which then stagnated over the following years. Customers came mainly from high-end manufacturing industries like the aerospace industry, which had driven the development from the beginning. The total value of shipments kept growing at this pace even after 1965⁸⁸.

The **second wave** in the 1970s and 1980s was triggered by the demand of microcomputers for numerical controls. Sales of NC machines grew strikingly by about 30 - 40% annually from 1978 to 1984.

Like the other two waves, the second wave was triggered off by major price cuts⁸⁹ and performance increases in the processor market. The price for a minicomputer CNC unit in 1973 had dropped roughly to 50% of that of a NC unit in 1963. The price of a microprocessor CNC unit in 1978 was only about a quarter of the price of a NC unit, and in 1982 the price for a multi-processor CNC unit was even below that.

The availability of US data allows the plotting of the increase in machine stock in one of the largest machine tool markets (see diagram below) for the period of the first and second wave. The curve shape resembles an “s” with inflection peaks in 1967, 1979 and in the mid-1980s. Around 1967 was the time when the first wave ebbed and initial fascination

⁸⁵ See p. 61 in Harless D. Wagoner, *The US Machine Tool Industry* (Cambridge, MA: The MIT Press, 1966).

⁸⁶ This is the reason why researchers often use data from the computer and related industries. Short reinvestment cycles make strong influences easily visible after a short period of time. Some researchers therefore termed this industry the “fruit fly” of business research.

⁸⁷ Compound Annual Growth Rate (CAGR)

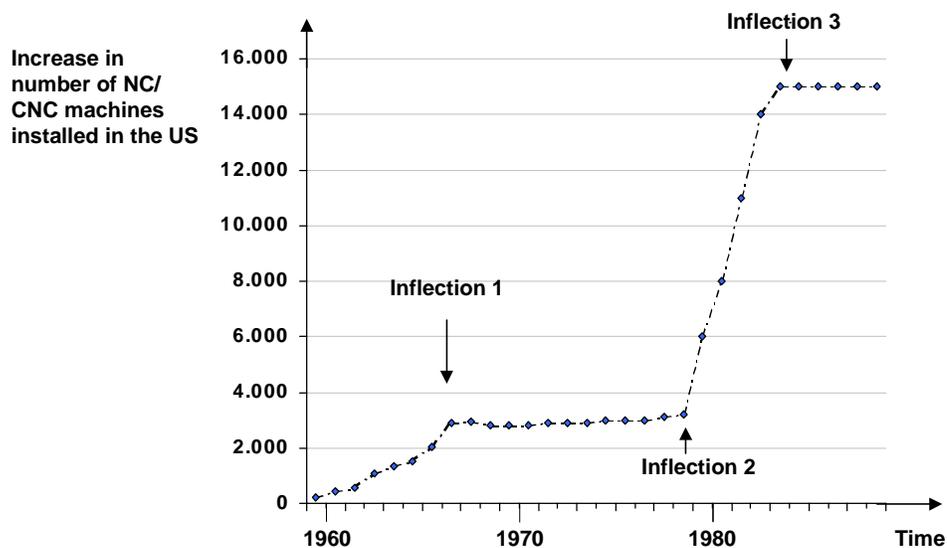
⁸⁸ Data is taken from USDoC, “Census,” (US Department of Commerce, 1959 - 1968).

⁸⁹ See graph p. 553 of Spur, *Vom Wandel der industriellen Welt durch Werkzeugmaschinen*.

about the new technology decreased. By that time the market niches for the application of hardwired NC machines had been occupied.

After 1967 there was no significant increase in demand until 12 years later when CNC machines were available in large numbers. These products offered new features and were far more flexible. By separating software from hardware the same control circuits could be built into different machines. For the older versions, every machine required its own type of control circuit. Now controls could be customized for different machine types by simply loading a new software program. In the same way, adapting to new shapes did not require exchanging the set of punched tapes and feeding new ones. The machines were prepared for new shapes through activating a different subroutine. The gain in flexibility and the drop in price made CNC machine tools interesting for the majority of the manufacturing industries. This interest expresses itself in another strong wave of demand, which lasted for over 5 years and ebbed off after 1984.

Diffusion of NC machines: Growth in stock



Source: US Department of Commerce, 1959 - 1968,
after 1968 estimates based on the American Machinist inventory of stock increase 1973, 1978, 1983 taken from
Ehrnberg, Ellinor, and Staffan Jacobsson, R & D Management 27, no. 2 (1997): p. 123

Seen in absolute numbers the second wave was much stronger than the first wave due to three main developments coinciding. The first development was, as discussed above, the emergence of a mass market. The “main stream” producers became interested and digitally controlled machines left their niches. Starting in 1980, digital control was also introduced for special machines⁹⁰ as well as for forming machines⁹¹, which had mostly been mechanically controlled until then. Few areas of chip-making metalworking, like gear cutting and threading, were left in which digital controls had not come to dominate yet. Naturally for these machines which did not require a lot of flexibility to begin with, the integration of NC technology happened with an offset of several years. This delay is partially responsible for the length of the waves. That means, when looking at the diffusion rate for one single machine type, the wave pattern for each category would have been even more obvious, although shifted in time.

The second development was around 1980 when Japanese companies started a massive invasion of the export markets, especially the US market. Section G of this article elaborates on Japan’s success. By focusing on highest economic gains for their customers, Japanese companies were able to capture a large portion of the world market. Ample supply of CNC machines that undercut the price of their Western competitors by over 50%⁹² contributed extensively to the standardization of the machines and thus to the availability of moderately priced CNC machines.

The third development was triggered by the effect computers had on the entire value chain⁹³. They enabled the transition from paper-based to electronic work in the drawing office (computer aided design – CAD) and led to efforts to support production with computers (computer aided manufacturing – CAM)⁹⁴. The ultimate goal was to integrate

⁹⁰ Mr. Hölzl, Ex-Hüller, Industry-Expert-Interview-Series, "Interview Series."

⁹¹ Mr. Passemard, Renault Automation, and Herr Brandstetter, Schuler Pressen, Ibid. Especially the extended machine environment, like the integration of automated work/ pallet changing systems and tool changers, require the use of numerical controls.

⁹² See price ratios on p.123 of Ehrnberg and Jacobsson, "Indicators of Discontinuous Technological Change: An Exploratory Study of two Discontinuities in the Machine Tool Industry."

⁹³ Afuah expanded Henderson’s concept for architectural innovation to the whole value chain. He expects that technological change that influences the conceptual design of products will have its influence throughout the value chain. Allan N. Afuah and Nik Bahram, "The Hypercube of Innovation," *Research Policy* 24 (1995): 51-76.

⁹⁴ Joel Feigenbaum, "Innovation in the Factory," *IEEE Spectrum* 17, no. 1 (1980): 54.

and automate the entire production process (computer integrated manufacturing – CIM). Some industry experts call it “input of raw material at the beginning of the production line and output of the finished product at its end”.

Investigations in Computer-Aided Design for Numerically Controlled Manufacturing Processes” was the title of a study at MIT, financed with over 3 million US\$ by the Air Force from late 1959 to 1970⁹⁵.

Many of the efforts of the national programs mentioned above, like the EXAPT society, aimed at promoting CIM but the problems soon appeared to be too complex to be solved entirely by computers⁹⁶. This first integration with the actual production machines was not successful on a broad base. Data handling was too complex and systems too rigid. With the amounts of data reduced, the efforts led to the implementation of production planning software, called PPS for production planning systems. These first systems simply assume unlimited resources to avoid the problem of handling massive streams of capacity data.⁹⁷ Modern extensions of this first step are ERP systems (enterprise resource planning), that include at least to some degree feedback from production infrastructure. But still, the CNC units were built from hardware and software that were proprietary systems and comparatively difficult to handle; special training was necessary.

The personal computer (PC), which started its triumphal march after a period of experimentation⁹⁸ in the early 1980s, meant standardized, cheaper, and easier to handle controls. The **third wave** of technological implementation continues into the present. PC based CNC appeared on the scene around 1990. The first models were too restricted in processing power and memory to handle the data amounts for sophisticated machines. They could at the most provide low cost alternatives for CNC machine retrofits. By 1994 these hurdles were surpassed by controls’ manufacturers like Siemens and Fanuc. PCs were

⁹⁵ For a detailed description see p. 94 – 133 in Reintjes, *Numerical Control: Making a New Technology*.

⁹⁶ Eugene M. Merchant, "Manufacturing - Yesterday, Today and Tomorrow," Working Paper - Institute of Advanced Manufacturing Sciences (2000).

⁹⁷ Oliver W. Wight, *Manufacturing Resource Planning: MRP II: Unlocking America's Productivity Potential* (New Jersey: Englewood Cliffs, 1982).

⁹⁸ For a historical account of the phase of technological fervent in the PC industry see Paul Ceruzzi, "From Scientific Instrument to Everyday Appliance: The Emergence of Personal Computers, 1970 - 77," *History and Technology* 13 (1996): 1-31.

embedded into CNC units⁹⁹. The more hardware oriented older programming languages are gradually being substituted by graphical user interfaces (GUI). The machine operator will eventually find himself in a Windows™-like PC environment. Producers started to exploit the possibilities of data transmission in local area networks (LAN) and accessing databases. Efforts to further standardize data will enable a further integration of design and production phase¹⁰⁰.

The information in the early systems flowed one-way - from the programmer to the PC, from the PC to the CNC, from the CNC to the machine. Producers like Yamazaki Mazak Corp.¹⁰¹ started considering PC operating systems like Windows NT™ as direct operating systems for the CNC unit itself. The PC is equivalent to the CNC and stores information about job schedules, setup instructions, statistical process control data, and machine diagnostics. The next step would be to connect the controls to the Internet¹⁰² and make the management of the production process independent of location.

The third wave is characterized by another change in the competitive landscape once again - German manufacturers regained ground in international competition, other European manufacturers such as Italian and Spanish companies play a more important role than before. In general most producers, even small ones, must be present in the international market. The technological development splits the market into two segments¹⁰³ - the first segment, high-efficiency production; the second, ultra modern technology (e.g. ultra-high speed, ultra-precision). In the high efficiency segment, in which Japanese manufacturers were able to establish a dominant position, companies from Taiwan¹⁰⁴, Korea, and China¹⁰⁵ are trying to set foot.

⁹⁹ Raymond E. Chalmers, "A Journey to Japan," *Manufacturing Engineering* 121, no. 3 (1998): 80 - 85.

¹⁰⁰ John Teresko, "Emerging Technologies," *Industry Week*, Mar 5, 2001 2001, 17 - 19.

¹⁰¹ Between 1994 and 1998 Yamazaki Mazak spent more than \$40 million and about 300 man years on a concept they call 'Cyber Factory'. Productivity gains for manufacturing companies by a factor of three are expected. Chalmers, "A Journey to Japan.".

¹⁰² DeJong, "All Machine Tools are not Created Equal."

¹⁰³ Keiichi Kawakami and Shinshichi Abe, "Machine Tools Build Prosperity for Related Industries/ Machine Tool Industry in Japan Today," *Business Japan* 30, no. 8 (1985): 89 - 97.

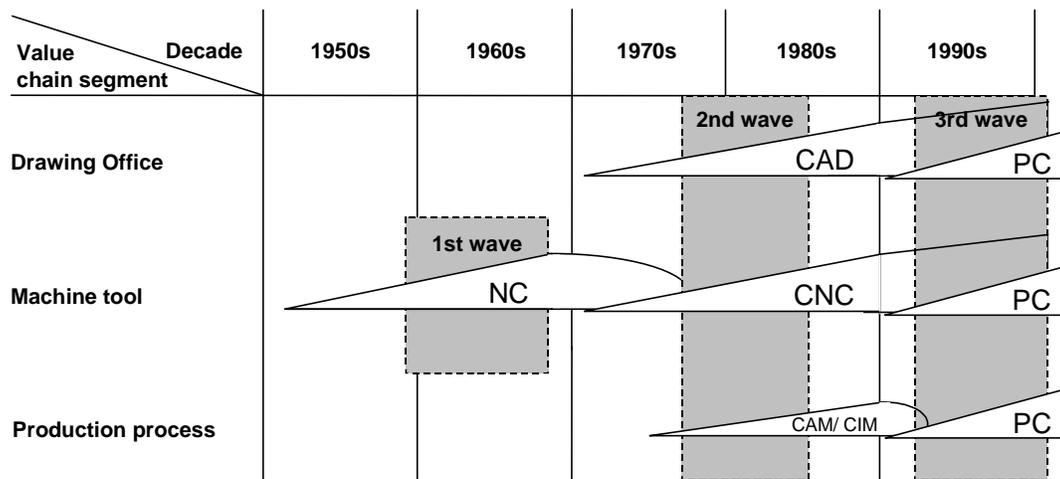
¹⁰⁴ Dorothy E. Jones and Otis Port, "The King of Knockoffs Rushes to Go from Imitation to Innovation," *Business Week*, Nov 26, 1984 1984, 188 - 192.

¹⁰⁵ By 1981, China's machine tool industry was already able to supply 99% of China's requirements of machine tool. Export of machine tools began at the end of the 1970s. In 1979 and 1980 China exported

Below is a scheme that gives an overview of the three shock waves that were caused by digital controls. It depicts the use of the various digital control technologies in vital segments of the production value chain - the design or drawing office, the machine tool production, and the use of the machine tool in the production process. The pointed end of each wedge represents the starting point of each technology. The diameter of the wedge illustrates the level of diffusion in its major areas of application.

The three waves of diffusion within the market are marked in gray. The first and second waves are located between significant inflections in the rate of diffusion as illustrated above using the example of the US market. The interview series revealed that the European market followed quite a similar pattern as far as time went.

Three waves of digital control technology



 Schematic representation of the extent to which the respective technology is used.

Source: Own depiction, based on discussions with Dzems M. Bruvelis, UBM, and Wilhelm Gauch, Alfing and various literature.

Among different manufacturing industries, however, the rate of diffusion varied considerably. Also the level of concentration in the respective customers industries seemed to influence diffusion. The number of different types of NC machines sold to

10,000 machine tools. Liang Xunxian, "China's Machine Tool Industry," *The China Business Review* 8, no. 6

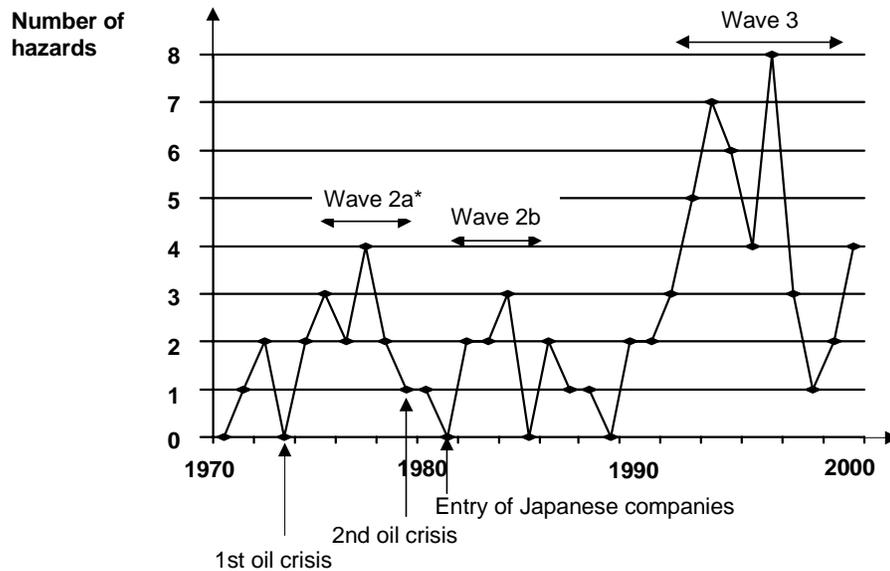
manufacturing industries during the three phases in general increased over 20 to 30 years each. This becomes evident when looking at the adoption rate for selected industries. The time frames from first use of NC machines to the time when 25% of all machine purchases are with NC technology can range between 6 and 15 years.¹⁰⁶ Thus in the chart above the wedges symbolizing the adoption of NC technology by the user industries, cover decades.

The detailed survey data from 59 international companies was analyzed to discover the extent of each wave character. For this reason three types of events were recorded throughout the history of the companies in the last 31 years. All of the companies were established in 1970. For every year the number of “hazards” or failures, i.e. bankruptcies, takeovers, or settlements with debtors, was added up and plotted over time. Overall 76 such hazards were counted, 35 out of 59 companies never experienced any of the three possible hazards. That means that 24 companies had repeated failures. Often take-overs follow bankruptcies and settlements. There are also some cases where initial failure did not make companies leave the market. The diagram below gives an overview of when the hazards occurred. Although small in size, the sample reflects the wave character of technology diffusion. Failures in the third wave are very much evident in the sample. The increase in failures is congruent with what was defined above as the start of the third wave in 1990. The second wave appears as two smaller “bumps” in the sample, named wave 2a and wave 2b. Wave 2a starts in the second half of the 1970s after the first “oil crisis” and lasts until around 1980. Wave 2b is just adjacent and ebbs off in the mid-1980s. The beginning of wave 2b is accompanied by the massive market entry of Japanese companies. Companies that experienced failure during wave 2b consisted mainly of producers of milling machines and lathes. Substitution happened especially in these segments. The first digitally machines which were successful on a broad base were machining centers and turning centers, substituting the classical milling machines and lathes.

(1981): 30 - 36.

¹⁰⁶ Romeo, "Interindustry and Interfirm Differences in the Rate of Diffusion of an Innovation."

Hazards in the sample of 59 international companies from 1970 to present (2001)



* esp. Grinding machines (also milling, lathes)

** esp. Milling and lathes (subst. by machining centers and turning centers)

Source: Own depiction based on sample of 59 machine tool manufacturers

The diffusion pattern of digital technology, numbers of the development of machine stock in the US as well as the hazard count in the survey of the 59 international companies are indicators for a technology shock in three waves. The interviews revealed that several smaller industry segments still undergo shocks caused by digital control technology ahead of them. Disruptions will potentially upset the competitive environment in these segments in a similar fashion as the three big waves did throughout the entire machine tool industry. For the sake of conciseness they are not being elaborated on here.

F. 2. Innovation of product architecture

In most of the cases the numerical control unit was retrofitted onto existing machine concepts until the ability of numerically controlled machines was fully understood and the machines completely redesigned. For the mechanical parts, the electronic control posed fundamental problems. The digital control was able to maneuver the tools at a much higher speed than the mechanics allowed. Soon it was understood that it was not an innovation of

only one component, of the control unit, the development had to involve the whole machine¹⁰⁷.

Additionally, numeric controls were able to improve or balance out the accuracy of mechanical parts. In addition NCs enabled companies to manufacture products that they had not been able to manufacture previously. First of all electronics replaced many mechanical functions (substitution). Then several functions were combined. It started with the combination of turning and other functions¹⁰⁸. Numerical controls enabled the integration of several functions into one machine and started a process of convergence from function specific machines to flexible machining centers (see figure below). In the 1960s, the functions of milling, drilling, planing, and boring could be combined into machining centers. The demand for versatile machines grew as lines in the production industry, e.g. the automotive industry, went from a small portfolio with few types in mass production to an increased type portfolio with smaller quantities. Later, with an additional increase in precision of NC systems, the functions of grinding and turning could be combined. The current developments allowed a convergence of turning centers and machining centers to appear realistic¹⁰⁹.

The combination of functions in one machine was achieved by changing the entire product concept. Numerical controls made it possible, not by putting together existing modules or improving existing machine types, but by understanding the capabilities of NCs and planning the machine architecture right from the start, i.e. the drawing board. According to Henderson's¹¹⁰ and Afuah's¹¹¹ categorization this indicates technological change of a large extent, called "architectural innovation".

¹⁰⁷ See "The lessons learned" p. 167 of Reintjes, *Numerical Control: Making a New Technology*.

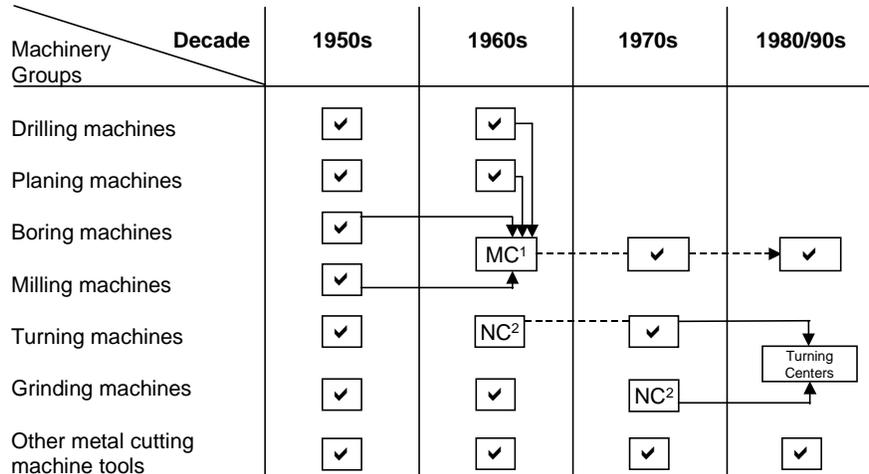
¹⁰⁸ Mr. Cuatto, Giana, Industry-Expert-Interview-Series, "Interview Series."

¹⁰⁹ Klaus Rietschel, Ex-Niles Chemnitz, Ibid.

¹¹⁰ Henderson and Clark, "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms."

¹¹¹ Afuah and Bahram, "The Hypercube of Innovation."

Convergence of cutting functionalities under the influence of NC



1) Machining centers, short MC. 2) Covers both NC and CNC.

Source: Own depiction, based on discussions with Dzems M. Bruvelis, UBM.

With different functionalities converging, the classical specializations of machinery group for cutting machine tools (as described in section C) disappeared to a large extent. In addition, the manufacturers were expected to supply more than just the machine. Customers preferred to buy entire systems from suppliers, including peripheral products and services - fixings, tools, set-up, training, service etc. Not only made convergence the borders of industry groups disappear, it also led to a redefinition of the market segments. As can be observed at recent industry exhibitions¹¹², producers are now rather divided into two large groups - the first group dealing with form-defining functionalities (drilling, planing, boring, milling) and the second group focusing on surface treatment (turning, grinding).

¹¹² At the EMO 2001 in Hannover milling machines, machining centers, flexible production systems, robotics were presented together in the exhibition halls as one group; in the other halls grinding machines and machines for honing, lapping, polishing, etc. were shown together. EMO, EMO Hannover - The World of Machine Tools - Catalogue.

F. 3. The technology's disruptive effect on companies' capabilities and the loss of competitive advantage

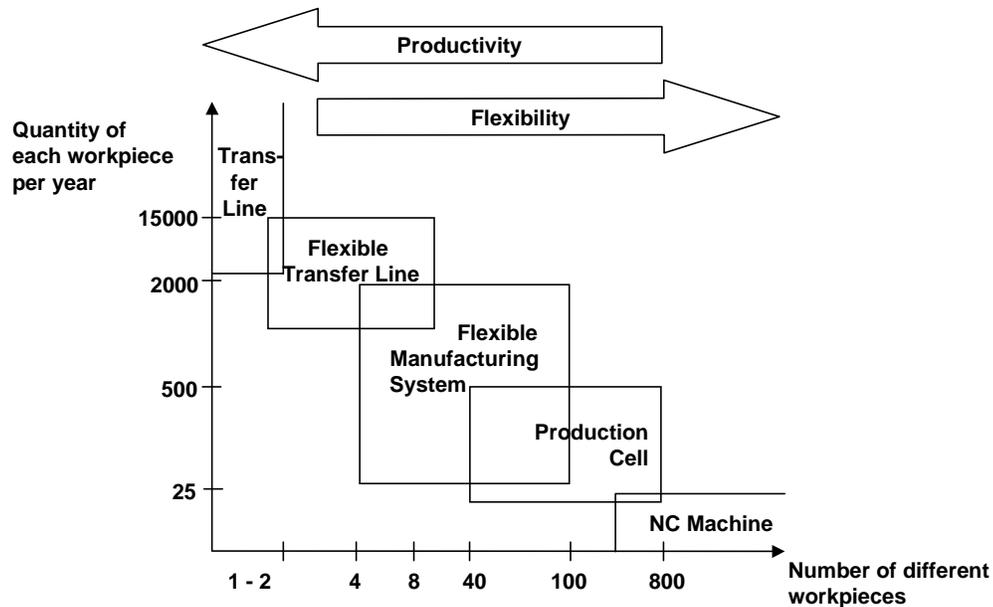
Naturally the new technology did not affect all producers of machine tools in the same way. The use of numerical controls gave machines first of all higher flexibility. Above all when workpieces are complex and require a number of different tool positions and movements, the programmable NC machine proved to be much more efficient than resetting the controls manually¹¹³ (see figure below). Equally when a large number of different workpieces were to be made on one machine, NCs proved to be superior¹¹⁴. The situation for high quantities of the same workpiece, however, was different. Here the production in "high-throughput" transfer lines - where durable mechanics are key - was more efficient. The advantages of NCs here were marginal¹¹⁵.

¹¹³ Pp. 149 – 156 in Carsten Dreher, *Technologiepolitik und Technikdiffusion: Auswahl und Einsatz von Förderinstrumenten am Beispiel der Fertigungstechnik*, ed. Rolf Funck and Werner Rothengatter, vol. 5, Karlsruhe Papers in Economic Policy Research (Baden-Baden: Nomos Verlagsgesellschaft, 1997).

¹¹⁴ A detailed discussion of different production principles is IAB FhG-ISI, IWF, *Der Einsatz flexibler Fertigungssysteme - Technische, einföhrungsorganisatorische, wirtschaftliche und arbeitsplatzbezogene Aspekte*, ed. KfK-PFT, vol. 41 (Karlsruhe: 1982).

¹¹⁵ Some authors claim that there has been a transition from CNC machine to the Flexible Manufacturing System. They fail to see that both exist concurrently and are just solutions which differ from each other by the degree of flexibility and efficiency they offer. In particular Ehrnberg and Jacobsson have even identified a discontinuity in this transition. In addition they diagnosed a discontinuity from conventional to CNC machine. This is a claim which is a bit coarse, but it is along the line of our observations. Ehrnberg and Jacobsson, "Indicators of Discontinuous Technological Change: An Exploratory Study of two Discontinuities in the Machine Tool Industry."

Overview of production concepts



Source: Own depiction, based on depiction p. 151 of Carsten Dreher, "Technologiepolitik und Technikfusion", Baden-Baden, Nomos Verlagsgesellschaft 1997

The result of the diffusion of the new technology was that NCs were introduced at a much earlier stage for applications that required high flexibility. For a while the machine tool industry was divided into two groups. First, there were companies that understood themselves as producers of machines for flexible use - second, companies that delivered high productivity lines.¹¹⁶ In recent years the main customers for transfer lines, the car industry, increased the variety of their models and sub-models so that their production lines needed more flexibility. Since then the producers of transfer lines are also under pressure to allow the lines to produce different workpieces.

As mentioned in the section on components of machine tools, before numerical controls the capability of producing machines with highly precise mechanical components was an important sales argument and a competitive advantage. For a rough idea of the situation, there were national differences in the accuracy of precision machines delivered

¹¹⁶ G. Moillet, COO, Mikron AG does not see the producers of transfer lines affected too much by effects of the NC technology. The control unit for high productivity lines does not require much flexibility but still highly accurate mechanics. Industry-Expert-Interview-Series, "Interview Series."

by the various companies¹¹⁷. In the 1950s, German companies produced machines, which served well for most accuracy requirements in the manufacturing industries. German producers were well known for their high standard of machines, especially in the automotive industries. It helped them to regain a strong position in international competition and even to become the number one exporter of machine tools in the 1970s.

Many Swiss companies, traditionally closely tied to the watch industry, focused on precision engineering. Their machines achieved accuracies suited for tasks requiring extreme quality of high surface and shape.

Manufacturers from the UK, USA, Italy¹¹⁸, Spain, and France had to make considerable efforts to improve the accuracy of their products.

Expert interviews helped to estimate an index that describes how large the differences were (see diagram below). If Germany would be the base with 100 points at the beginning of the 1950s, several Swiss companies responsible for the country's high quality image¹¹⁹, would be rated at above 120 points. Companies with some output problems such as UK, US and Italian companies would lie at around 80 points. Through increased efforts to enhance production procedures, conventional machines from these countries would have narrowed the gap between them and Germany and Switzerland.

The capabilities of probing systems and adaptive behavior of CNC machines basically put most of the producers, including the Japanese companies, on the same level of machine accuracy. Two techniques were instrumental for a quantum leap in workpiece accuracy. Firstly, geometrical shortcomings of machines could be corrected via input of correction values into the software. Secondly, temperature caused expansion of workpieces and machines could be corrected in process with the aid of probing systems. The skill to produce highly exact mechanical parts and the knowledge of "tricks" about how to deal mechanically with expansion due to temperature became less important. The new control technology had a large impact on companies' competence¹²⁰ required for a successful

¹¹⁷ Dr. Klein, Ex-Burkhardt&Weber, and Prof. Weidemann, Ex-VDF and Ex-Pittler, Ibid.

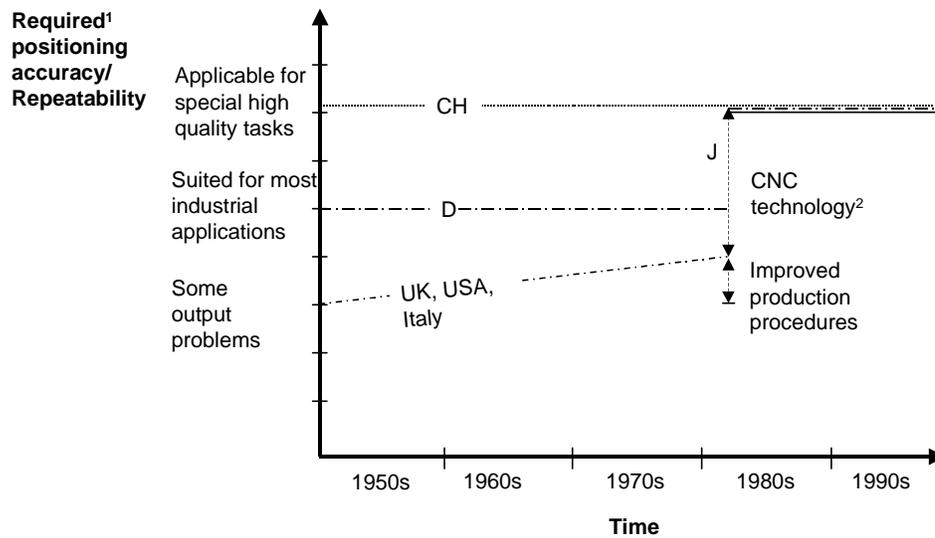
¹¹⁸ Also Spain and France.

¹¹⁹ Like the company Dixi Machines SA.

¹²⁰ For the importance of competence when technological change happens see Tushman and Anderson, "Technological Discontinuities and Organizational Environments."

machine tool market, dramatically devaluating the old competence accrued over generations.

Development of positioning accuracy under the influence of CNC and in-process measuring



1 Qualitative, based on expert interviews

2 With automatic feedback loop from measurement unit.

Source: Own depiction, based on expert interviews and discussions with Dzems M. Bruvelis, UBM

Since the invention of machine tools, it was the mechanical engineer who had brought the critical knowledge into the design of machines. Particularly when it came to durability and accuracy of the products, experience in good mechanical design paid off. The advent of digital control systems brought about a need for electrical and electronic competence within the machine tool companies. The emphasis in companies not only shifted from specialized to standardized mechanics¹²¹ but also overall from mechanics to electronics. Electrical engineering departments were created whose responsibility was either to modify standard numerical controls or, in addition, to develop specific controls and to plan the integration of machines into automated processes. In most cases though, vertical disintegration took place. The machine tool manufacturers no longer produced the control unit. Usually only so much competence was built up in-house as to allow

integration of digital controls into the machines and the integration of the machines into automated production lines. At the 1965 Machine Tool Builders' Show in Chicago it became evident that the value chain for machine tools had experienced a major change. Control units no longer fell into the machine tool builders' competence, they were mostly developed and supplied by electronics companies in the US such as General Electrics, Bunker-Ramo and Superior Electric¹²², later also by companies like Fanuc in Japan and Siemens¹²³ in Germany.

At the other end of the production chain, the companies at the same time decreased their depth of vertical integration due to cost pressure¹²⁴ and increased the percentage of mechanical components. These parts were bought from cheaper, specialized suppliers, sometimes from low-waged countries.

F. 4. Change in the product's value proposition and order of magnitude improvement in value for users

For years, accuracy had been one important barrier to entry into the market. Buyers were extremely brand aware; the established companies had the image of producing accurate machines of high quality. NC rendered this image rather worthless. Electronic controls now enabled most companies to manufacture machines that could produce at a

¹²¹ Mr. Richard Curless, Cincinnati Machine, and Mr. Rainer Nehls, Mercer Management Consulting, Industry-Expert-Interview-Series, "Interview Series."

¹²² See p. 161 Reintjes, *Numerical Control: Making a New Technology*.

¹²³ Detailed case studies on the development at the MIT, at Fanuc, and at Siemens were performed by the working group "Culture and Technical Innovation" at the Academy of Sciences and Technology in Berlin, and published in Günter Spur, Dieter Specht, and Sascha Schröder, "Case B: Die Numerische Steuerung (NC-Machine Tools)," in *Culture and Technical Innovation: a Cross-Cultural Analysis and Policy Recommendations*, ed. The Academy of Sciences and Technology in Berlin (Working Group: Culture and Technical Innovation), Research Report (Berlin: Walter de Gruyter, 1994), 621 - 735. One of the authors built his doctoral thesis on this research: Sascha Schröder, *Innovation in der Produktion: eine Fallstudienuntersuchung zur Entwicklung der numerischen Steuerung*, ed. Günter Spur, vol. 168, *Produktionstechnik - Berlin, Forschungsberichte für die Praxis* (München, Wien: Carl Hanser Verlag, 1995).

¹²⁴ Ulrich Vetter confirmed the fact that it was cost pressure that led to the vertical disintegration for mechanical parts: Industry-Expert-Interview-Series, "Interview Series." It was not that the increase in quality by suppliers has prompted machine tool companies to out-source. This was misunderstood in Rendeiro, "How the Japanese Came to Dominate the Machine Tool Business." The increase in mechanical quality had happened earlier (until the early 1980ies), but inside the machine tool companies themselves (see second figure in section F. 3.).

level of accuracy, which was even above market demand. The decision criteria to purchase a machine tool had changed.

Price inflation of microprocessors and electronic memory led to a drop in price for NC units (see section F. 1.) This allowed Japanese companies that had focused from the beginning on the integration of computers in the control units of standard machines, to offer CNC machines in great volume at low prices. The Japanese companies could play out their price advantage¹²⁵ and successfully entered the world market. They even overtook Germany as the largest supplier of machine tools¹²⁶.

As case studies in manufacturing industries suggest¹²⁷, there is a number of advantages that customers of CNC machines value. The manufacturing and non-manufacturing related benefits, which are displayed in the diagram below, result in an order of magnitude advantage for users.

¹²⁵ Dzems Bruvelis, UBM, Industry-Expert-Interview-Series, "Interview Series."

¹²⁶ The Japanese approach was soon understood by the German industry. Consulting projects in the late 1970s initiated by the German machine tool association VDW and by large manufacturers like Deckel and Maho identified the scale advantages of CNC mass production of standard machines. One effort to create a German mass producer was the merger of Deckel and Maho, but resulted in the failure of the new firm. Gildemeister, strongly supported by their financiers, took over the remnants in 1994. Sources: VDW, Dr. Heinz Drink, etc. in Ibid.

¹²⁷ Nicholas S. Vonortas and Lan Xue, "Process innovation in small firms: case studies on CNC machine tools," *Technovation* 17, no. 8 (1997): 427-438.

Reasons for introducing computer numerically controlled machines

Manufacturing related benefits

- Integration of operations
- Increased effectiveness
- Increased quality
- Decreased downtime
- Shorter lead time
- Decreased scrap
- Decreased rework
- Decreased number of setups
- Decreased inspectors
- Better queuing
- Experience gained
- Wider volume of production
- Increased capacity
- Decreased handling

Non-manufacturing related benefits

- Increased quality
- Increased customer goodwill
- Decreased lag between order and delivery
- Helps assure competitiveness
- Cost competitiveness
- Better customer service
- Increased growth opportunities

Source: Own depiction, based on Vonortas, Nicholas S., and Lan Xue. "Process Innovation in Small Firms: Case Studies on Cnc Machine Tools." *Technovation* 17, no. 8 (1997): 427-38.

To quantify the advantages, we can take the amount of money customers were willing to spend on numerical machine tools. Around 1970, customers on average spent five times more on a NC machine than on a classical mechanical one¹²⁸. Towards the end of the 1970s the ratio was even more extreme. According to the US census the average price for a NC machine was 190.000 US\$, whereas the prices for a purely mechanical machine was between 5.000 and 50.000 US\$¹²⁹. The example of cylinder grinding machines illustrates this. The NC version would cost around half a million US\$, whereas a purely mechanical machine for the same purpose would sell for only about 50.000 US\$ - a factor of 10. For a long time, the customer's motto was "If you have a good product, you can afford a NC machine"¹³⁰. Literature has also identified the price performance ratio as one of the strongest indicators for technological change. Neither patents nor bibliometrics can give

¹²⁸ Numbers from USDoC, "Census."

¹²⁹ Numbers from Ibid. And Marx, "Technological Change in the Structure of the Machine Tool Industry."

¹³⁰ Dr. Zoltan Szabo, Ex-Hüller-Hille, Industry-Expert-Interview-Series, "Interview Series."

early warnings. These indicators rather follow than precede the innovation and the subsequent diffusion process¹³¹.

The increase in value also left its trace on the diffusion pattern of NC technology in the customers' industries. Large manufacturing companies replaced their machine arsenal more quickly with machines which had the new control technology, a trend which lasts until today. The usage of NC machines in companies with more than 1000 employees is more than double than in companies with 100 employees and less.¹³² The price of a NC machine might simply be too high for many small companies.

G. *The Japanese success story*

Along with the technological change came the market success by Japanese machine tool manufacturers. Originally Japanese manufacturers produced machines under licensing agreements with foreign companies. For example Mitsubishi Heavy Industries bought technology to make copying lathes from the Swiss company Oerlikon, boring and milling machines from the Italian company Innocenti and gear hobbing machines from the German company Lorenz¹³³ between 1954 and 1961.

As we saw before, customer's brand awareness and the perceived high level of mechanical accuracy of the established companies posed a barrier to a market entry for new manufacturers of machine tools. But with the advent of numerical controls these barriers disintegrated more and more. Price became the dominant feature of competition. Between 1970 and 1980 the price on average for a Japanese NC machine tool was half or one third of the price of a comparable US produced machine¹³⁴. On the one hand the Japanese price advantage was amplified by comparatively low wages¹³⁵ for a long time. On the other hand, as mentioned in the section on NC's disruptive effect on companies' capabilities, the

¹³¹ Ehrnberg and Jacobsson, "Indicators of Discontinuous Technological Change: An Exploratory Study of two Discontinuities in the Machine Tool Industry." And J. Schmookler, "Economic Sources of Inventive Activity," *The Journal of Economic History* 23, no. 1 (1962): 1 - 20.

¹³² See results of survey from 847 companies, p.143 of Dreher, *Technologiepolitik und Technikdiffusion: Auswahl und Einsatz von Förderinstrumenten am Beispiel der Fertigungstechnik*.

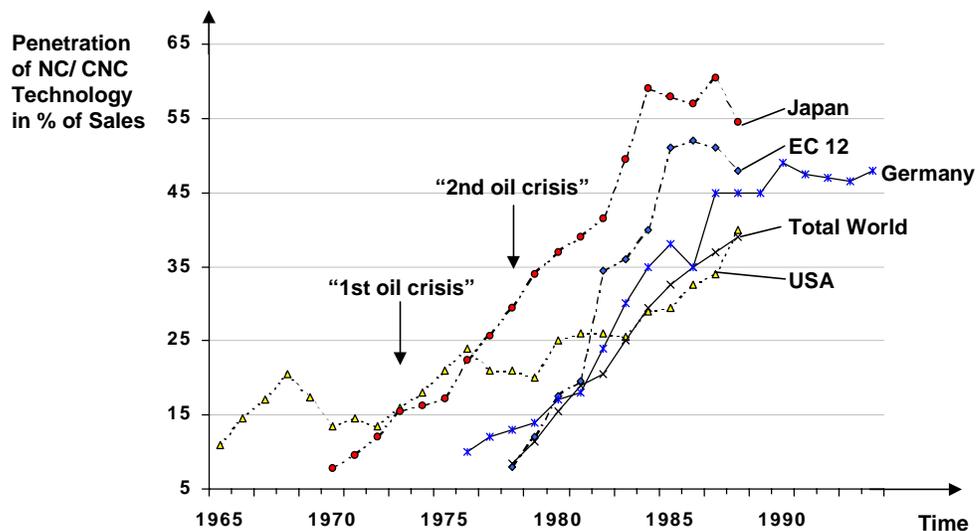
¹³³ Lee, "The role of user firms in the innovation of machine tools: The Japanese case."

¹³⁴ Mazzoleni, "Learning and Path-Dependence in the Diffusion of Innovations: Comparative Evidence on Numerically Controlled Machine Tools."

¹³⁵ Unger, "Industrial America: Strategies for Recovery in Machine Tool Industry."

Japanese had at an early stage focused on NC technology and the integration of computers in the control unit. In the 1970s the percentage of numerically controlled machine tools versus the total number of machine tools was 20% in Japan, whereas the number for European and US manufacturers was 10% (see figure below)¹³⁶.

Levels of NC penetration in the important producer countries



Source: Own depiction based on data from VDW, Strategic Study on EC Machine Tool Sector, WS Atkins Management Consultants in assoc. with Ifo-Institut, Numbers 1976, 1977, 1990, 1991 from Am. Machinist, Numbers before 1979 from Roberto Mazzoleni (1997), Germany data from Schwab (1996)

Whilst US companies failed to benefit from their early lead in the technology, Japanese companies followed their goal systematically. Also and especially during the years of the two oil crises in the 1970s when other companies reduced their commitment to new technologies, Japanese companies pushed NC/ CNC technology. The share of digitally controlled machines sold rose steadily.

Machining centers were designed as standard machines with very few options or peripheral equipment for the customer to chose from. Worldwide marketing and a small number of variants allowed for high quantities in production. The diffusion of the new

¹³⁶ Numbers taken from AMT, The Economic Handbook of the Machine Tool Industry (McLean, Virginia: AMT - The Association for Manufacturing Technology, 1990), VDW, "Strategic Study on EC Machine Tool Sector."

technology overtook the US numbers in 1976 and remained at the highest level in the world from then on. Supported by a favorable exchange rate, the percentage of all machine tools worldwide produced in Japan grew from 13% in 1976 to 30% in 1980. For the European Community (EC10), which then, with the exception of German companies, was mainly competitive in the European market and even lost ground there¹³⁷, that number dropped from 41% to 35%. As we have seen in sections A and F. 1., this was at the time of the second technology wave, when the US also lost its market leadership position. At the same time the number of all machine tools produced in the US went down from 38% to 24%¹³⁸. The success of the Japanese companies had such a strong influence on the minds of decision-makers that some of them regard Japan as the catalyst of the market evolution since 1978¹³⁹.

Japan's entry of machine tool users into the market for machine tools was unique. With car production growing, car assemblers established their own subsidiaries or strengthened their machine divisions to produce the machines they needed¹⁴⁰. Toyoda established a subsidiary, Toyoda Koki, in 1956 to produce transfer lines, and Nissan Motor cooperated with its member company Hitachi Seiki for the same purpose. Equally Mazda Motors started to make transfer machines in its machine division¹⁴¹. This development was seen as a national effort and largely encouraged by MITI, the Japanese Ministry for International Trade and Industry. In the early years of the development, MITI provided focused resources for the transfer of technological know-how to Japan.

The successful entry of user firms is also being attributed to "keiretsu", the conglomerate structure of Japanese industry. Risk sharing and collaboration made it less vulnerable to short-term performance pressures. Entries from various sectors increased the number of firms which were engaged in manufacturing metal-cutting machine tools from

¹³⁷ Anonymous, "Special Series 1985: Europe's Machinery Industries - Report No. 2: New Technology and Innovation," *European Trends*, no. 2 (1985): 38 - 53.

¹³⁸ Harrop, "Crisis in the Machine Tool Industry: A Policy Dilemma for the European Community."

¹³⁹ Robert Seach, Hardinge, Industry-Expert-Interview-Series, "Interview Series."

¹⁴⁰ An Interview with Mr. Okitoma and Mr. Yoshida from Mitsubishi Heavy Industries at the EMO 2001 revealed that the Machine Tool Division's primary task still is to supply equipment for the special purposes of Mitsubishi Motors. The division still works in quasi cost center structure. Sales outside of Mitsubishi are just to use excess capacity. Ibid.

¹⁴¹ Lee, "The role of user firms in the innovation of machine tools: The Japanese case."

108 in 1951 to 351 in 1959 and to 671 by 1969, an annual growth of about 10%. During the 1970s this number rose again by 6.7%.¹⁴² In the 1980s electronics companies entered the market and made an effort to incorporate minicomputer technology into the control of machine tools. The great success of Japanese companies is often attributed to this effort. The prominent example is Fujitsu. This company established an independent firm, Fujitsu-Fanuc, in 1972 based on its development division for computer-control devices. Its task was to market this technological asset. Fanuc became the leading producer of NC controls by the end of the 1980s, with 50% of the world market share and 80% of the market share in Japan¹⁴³.

At Fujitsu-Fanuc worked also the embodiment of Japanese NC technology, Dr. Seiueemon Inaba, the future president of Fanuc. He had received the plans of the NC project at MIT and successfully completed a reproduction of such a machine in 1957. With a simplified control unit architecture, Fanuc soon came to dominate the Japanese market¹⁴⁴. The Japanese production focused on narrowly defined product offerings of relatively simple machine tools, whereas more complicated ones were traditionally imported from German, Swiss and US companies.

H. External factors

Unfavorable **exchange rates** hit the US machine tool industry especially hard in the 1990s. With a strong value of the US dollar compared to the European and Japanese currencies, US manufacturers faced a cost disadvantage they could hardly match. In the second half of the 1990s, the European currency union helped stabilize European exchange

¹⁴² Ibid.

¹⁴³ Ibid.

¹⁴⁴ For anecdotal evidence on the Japanese control unit design and their effect on the diffusion see Mazzoleni, "Learning and Path-Dependence in the Diffusion of Innovations: Comparative Evidence on Numerically Controlled Machine Tools.": At a joint project with Makino Milling a control unit in open-loop design which was commercialized in the mid-sixties. The closed-loop architecture of MIT contained in addition to open-loop a feed-back circuit from the work table to the command unit to increase positioning accuracy. Leaving out this rather complex element for the open loop design promised cheaper control units. To achieve the same accuracy without feedback circuit, the performance of the stepping motor had to be improved. In fact, the technical key parameters of step motors like stepping rate and torque output improved between 20 and 40 times. The closed-loop design dominated the Japanese machine architecture focusing on low cost until the early 1970s. For international markets, though, the closed loop approach was followed again.

rates amongst them and put them at a comparatively low value – a development welcomed by the European producers¹⁴⁵.

The dollar value had decreased already during the **oil crises** of the 70s (19 October 1973 and 8 November 1978). The crises started recessions that had negative effects on European machine tool exporters and hit the industry of Europe and the United States with a two to three year delay. Demand dropped and there was over-capacity. The Western manufacturers perceived it as the first tangible crisis since the Second World War. Cash for technological development, establishing know-how and training, etc. and even the financing of new orders became difficult. Some companies that were financially not sound enough, such as Burr and Hüller in Germany, went out of business or were bought up¹⁴⁶.

Also, the **collapse of the East Block** after 1990 meant a loss of an important export market. Although business with Eastern Europe always meant a high level of risk, the political and economical changes in the East affected German companies in particular. The economic change coincided with the worldwide economic crises, which in Germany was partially covered by increased investment activities in the former German Democratic Republic¹⁴⁷ after the reunification. As a result of the economic crisis, cost awareness became the top priority for most manufacturing companies. Suppliers of the car industry experienced the “Lopez-effect” of meeting extreme cost goals¹⁴⁸.

With some restrictions in international trade, the **Gulf War** in 1991 had a negative impact on export-oriented industries. At this time the machine tool industry had followed the general trend of the manufacturing industry towards **globalization**. Thus the effects of slow orders could be felt everywhere¹⁴⁹, quite a contrast to the effects at the time of the

¹⁴⁵ Mr. Abler, Liebherr, Industry-Expert-Interview-Series, "Interview Series."

¹⁴⁶ Wilhelm Gauch, Ex-Burkhardt&Weber, Dieter Hofmann, Ex-Heckler&Koch.

Hüller became in 1975 key element of Thyssen Production System's chip-making machinery business. Over the time Burr special machines, Hille machining centers, Diedesheim special machines, Hessap lathes, Witzig&Frank special machines, Cross special machines, and Giddings&Lewis machining centers were added to the product portfolio. The respective companies were taken over. Hans Ulrich Jaissle, Ex-Hüller, Ibid.

¹⁴⁷ Ludwigsburger Maschinenbau GmbH Burr, who designed the first multi-spindle application, got into severe financial problems after a contract with the Soviet Union was not kept. Helmut Schneider, Ex-Burr, and Alfred Häcker, EMAG, Ibid.

¹⁴⁸ Dr. Lothar Ophey, Ex-ExCello, Ibid.

¹⁴⁹ Werner Babel, Ex-Maho, Dr. Udo Schapp, Gleason-Hurth, Dr. Walter Eggert, Gleason-Pfauter, Ibid.

Korean War that had led to an increased demand in the US in the at that time regionally structured manufacturing markets of the 1950s.

In some countries the strong position of **labor unions** restricted the flexibility of companies' resource allocation. In Germany there was much of a discussion about overtime and vacation time. A change of workers' rights in these areas was still taboo. For the financially burdened companies, personnel costs of over 40%¹⁵⁰ without much possibility to allocate them flexibly to demand, remained a structural disadvantage versus countries with less formalized workers' rights. By contrast, in Japan to date the availability and flexibility of work force is taken as given¹⁵¹.

Another factor that left its imprint on the success of the medium-size, family-run businesses is the **ownership structure**¹⁵². Constellations where a member of the family who controls the majority of shares is at the same time managing the business seem to be prone to the risk of extreme decisions; either radical change or no change at all.

As we have seen in this section, external factors and the dependence of national and world economic trends contribute to some of the changes in the competitive landscape in the machine tool industry. None of these factors, though, overweigh the effects of technological change as discussed in the sections above¹⁵³. They rather amplify the effect of technology shock. Therefore the base hypothesis that technological change is the main trigger for the turbulence within this market still holds good.

I. Conclusion

The introduction of numerical controls was much less an evolutionary process than a series of technology shocks that struck in three waves. Established companies in many cases failed to judge the full extent of change. The vanishing of leading companies from their dominant position cannot be attributed to consolidation within the industry. Due to a

¹⁵⁰ VDMA, "Kennzahlenkompass," (Frankfurt am Main: Verband deutscher Maschinen- und Anlagenbau e.V., 1993).

¹⁵¹ Yushiyuki Kanesige, Mori Seiki, Prof. Dr. Franz Klenger, Ex-Gildemeister, Ex-Heidenreich&Harbeck, Industry-Expert-Interview-Series, "Interview Series."

¹⁵² Frank Baumbusch, Ex-Pittler, Witzig&Frank, Ibid.

¹⁵³ Most of the experts agree with this conclusion. See for example Klaus Rietschel, Ex-Niles Chemnitz, Ibid.

traditionally confusingly diverse product variety, scale effects on the production side are merely present - size counts when it comes to financial issues.

The turbulence in the market appeared to have occurred to a large extent due to technological change. The market segments themselves were redefined through convergence of functionalities and the integration of the machine environment into systems. Three categories serve well to identify shocks - changes in the product architecture, changes in competence that lead to competitive advantage, and changes in the value proposition as well as the way the value of the product is perceived. The industry in the UK is an example where technology was not observed carefully enough and where it has not received adequate attention.

The success of the Japanese and the failure of many US companies tell us that focusing systematically on the order-of-magnitude economic gain for the customer is more important than the location of invention. Several manufacturers, however, misunderstood that considering all potential options a customer might desire does not necessarily lead to the customer's greatest possible benefit. Customers do not really expect a thicket of different options and technical flavors to choose from, they simply want the best in overall price and performance for the whole life cycle of a production system.

The technological change occurred in three waves, of which the last one is still ongoing. PC environments, networking capabilities and the expectation to hook up production systems to the Internet have the potential to further upset the current market structure in a way similar to the recent history of the machine tool industry.

*Appendix I: Industry experts in interview series*¹⁵⁴

- Mr. Johannes Abler, Managing Director, Liebherr (D)
- Mr. Fernando Arocena, Commercial Director, Soraluze – Grupo Danobat (Es)*
- Mr. Werner Babel, former CEO, MAHO (D)
- Mr. Frank Baumbusch, former CTO, Pittler AG (D), Managing Director, Witzig&Frank – Thyssen Krupp Production Systems (D)
- Mr. Peter Baumgartner, Director Marketing & Sales, Schneeberger (CH)*
- Mr. Peter Baumgartner, Managing Director Germany and Head of Manufacturing Group, Mercer Management Consulting (D/ US)*
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Appendix II: References

- Ackermann, Charbel, and Jeffrey Harrop. "The Management of Technological Innovation in the Machine Tool Industry: a Cross-national regional survey of Britain and Switzerland." *R&D Management* 15, no. 3 (1985): 207 - 218.
- Afuah, Allan N., and Nik Bahram. "The Hypercube of Innovation." *Research Policy* 24 (1995): 51-76.
- AMT. *The Economic Handbook of the Machine Tool Industry*. McLean, Virginia: AMT - The Association for Manufacturing Technology, 1990.
- . "World Market Shares." *American Machinist* (1984): 2.
- Anonymous. "Bring Technology Out of the Lab and Into Your Plant." *Production* 86, no. 2 (1980): 83.
- . "Special Series 1985: Europe's Machinery Industries - Report No. 2: New Technology and Innovation." *European Trends*, no. 2 (1985): 38 - 53.
- Archibugi, Daniele, and Roberto Simonetti. "Objects and Subjects in Technological Interdependence. Towards a framework to monitor innovation." *International Journal of the Economics of Business* 5, no. 3 (1998): 295 - 309.
- Arnold, Heinrich M. "Can great companies survive technology shocks? - A literature overview." *Munich School of Management, Electronic Working Paper Series*, no. 1/2001 (2001).
- Arnott, Deborah. "The British Machine Tool Trauma." *Management Today* (1983): 72 - 80.
- Ashburn, Anderson. "Blue Bulletin." AMT - The Association for Manufacturing Technology, *American Machinist*, 1972-2000.
- BCG. "Europastudie für ausgewählte Zielländer - Dokumentarband." Verein Deutscher Werkzeugmaschinenfabriken e.V. -VDW, 1990.
- Ceruzzi, Paul. "From Scientific Instrument to Everyday Appliance: The Emergence of Personal Computers, 1970 - 77." *History and Technology* 13 (1996): 1-31.
- Chalmers, Raymond E. "A Journey to Japan." *Manufacturing Engineering* 121, no. 3 (1998): 80 - 85.
- Christensen, Clayton M. *The Innovator's Dilemma: When New Technologies Cause Great Firms To Fail*. 1 ed, *The management of innovation and change series*. Boston: Harvard Business School Press, 1997.
- . "The Rigid Disk Drive Industry: A History of Commercial and Technological Turbulence." *Business History Review* 67, no. 4 (1993): 531-558.
- Daly, Anne, and Daniel T. Jones. "The Machine Tool Industry in Britain, Germany, and the United States." *National Institute Economic Review*, no. 92 (1980): 53.
- de Figueiredo, John M., and Margaret K. Kyle. "Surviving the Gales of Creative Destruction: The Patterns of Innovative Activity in the Desktop Laser Printer Industry." *MIT Sloan Working Paper* (2000).
- DeJong, Colleen A. "All Machine Tools are not Created Equal." *Automotive Manufacturing & Production* 110, no. 3 (1998): 78 - 81.
- Dreher, Carsten. *Technologiepolitik und Technikdiffusion: Auswahl und Einsatz von Förderinstrumenten am Beispiel der Fertigungstechnik*. Edited by Rolf Funck and

- Werner Rothengatter. Vol. 5, *Karlsruhe Papers in Economic Policy Research*. Baden-Baden: Nomos Verlagsgesellschaft, 1997.
- Ehrnberg, Ellinor, and Staffan Jacobsson. "Indicators of Discontinuous Technological Change: An Exploratory Study of two Discontinuities in the Machine Tool Industry." *R & D Management* 27, no. 2 (1997): 107-126.
- EMO. *EMO Hannover - The World of Machine Tools - Catalogue*. Vol. 14. Hannover: Generalkommissariat der 14. EMO Hannover, Messegelände, 2001.
- Eversheim, Walter, Wilfried König, Manfred Weck, and Tilo Pfeifer. *Anschriften der Freunde und ehemaligen Mitarbeiter des Laboratoriums für Werkzeugmaschinen und Betriebslehre der Rheinisch-Westfälischen Technischen Hochschule Aachen*. Edited by Herwart-Opitz-Haus Laboratorium für Werkzeugmaschinen und Betriebslehre der Rheinisch-Westfälischen Technischen Hochschule Aachen. Aachen, 1980.
- Expert, Industry. Personal Interview 2000-2001.
- Fawcett, Clifford W., and Dan Roman. "Industry Overview for the Purchaser of Machine Tools." *Journal of Purchasing and Materials Management, Fall 1976* (1976): 8-14.
- Feigenbaum, Joel. "Innovation in the Factory." *IEEE Spectrum* 17, no. 1 (1980): 54.
- FhG-ISI, IAB, IWF. *Der Einsatz flexibler Fertigungssysteme - Technische, einführungsorganisatorische, wirtschaftliche und arbeitsplatzbezogene Aspekte*. Edited by KfK-PFT. Vol. 41. Karlsruhe, 1982.
- Fleischer, Manfred. *The Inefficiency Trap: Strategy Failure in the German Machine Tool Industry*. Edited by Edition Sigma. Berlin: Wissenschaftszentrum Berlin für Sozialforschung - WZB, 1997.
- Farrant, Robert. "Good jobs and the Cutting Edge: The U.S. Machine Tool Industry and Sustainable Prosperity." *Working Paper - University of Massachusetts Lowell*, no. 199 (1997): 1 - 30.
- Glunk, Fritz R. *100 Jahre Pittler 1889 - 1989*. Edited by Prof. Dr. Dieter Weidemann - Vorsitzender des Vorstandes der Pittler Maschinenfabrik AG. Langen: Britting Verlag, 1989.
- Harabi, Najib. "Innovation through vertical relations between firms, suppliers and customers: A study of German firms." *Industry and Innovation* 5, no. 2 (1998): 157 - 172.
- Harrop, Jeffrey. "Crisis in the Machine Tool Industry: A Policy Dilemma for the European Community." *Journal of Common Market Studies* 24, no. 1 (1985): 61 - 76.
- Henderson, Rebecca M., and Kim B. Clark. "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms." *Administrative Science Quarterly* 35, no. 1 (1990): 9-30.
- Hine, Charles R. *Machine Tools for Engineers*. 2 ed. New York, Toronto, London: McGraw-Hill Book Company, Inc., 1959.
- Hsu, Shiow, and Pao-Long Chang. "Promoting Technological Capabilities of Small and Medium-Sized Enterprises through Industry-University Cooperation: Case Study of Taiwan Machine Tool Industry." *International Journal of Manufacturing Technology and Management* 1, no. 2,3 (2000): 257 - 270.
- Industry-Expert-Interview-Series. Personal Interview 2000-2001.

- Jones, Dorothy E., and Otis Port. "The King of Knockoffs Rushes to Go from Imitation to Innovation." *Business Week*, Nov 26, 1984 1984, 188 - 192.
- Kawakami, Keiichi, and Shinshichi Abe. "Machine Tools Build Prosperity for Related Industries/ Machine Tool Industry in Japan Today." *Business Japan* 30, no. 8 (1985): 89 - 97.
- Klepper, Steven. "Entry, Exit, Growth, and Innovation over the Product Life Cycle." *American Economic Review* 86, no. 3 (1996): 562-583.
- Klump, Rainer, and Beate Männel. "'Lange Wellen' der Unternehmenskonjunktur." *Zeitschrift für Unternehmensgeschichte* 40, no. 1 (1995): 1 - 34.
- Kuba, Yasunori. *Meister der Fertigungstechnologie - Die 70jährige Geschichte von Mazak*. Taito-ku, Tokyo: Yamazaki Mazak Corp., 1989.
- Lee, Kong Rae. "The role of user firms in the innovation of machine tools: The Japanese case." *Research Policy* 25 (1996): 491-507.
- Marx, Thomas G. "Technological Change in the Structure of the Machine Tool Industry." *MSU Business Topics* 27, no. 1 (1979): 41-47.
- Mazzoleni, Robert. "The Agency System in the International Distribution of U.S. Machine Tools, 1900 - 1915: Social Norms and Contracts." *Business and Economic History* 27, no. 2 (1998): 420 - 430.
- Mazzoleni, Roberto. "Learning and Path-Dependence in the Diffusion of Innovations: Comparative Evidence on Numerically Controlled Machine Tools." *Research Policy* 26, no. 4,5 (1997): 405 - 428.
- Merchant, Eugene M. "Manufacturing - Yesterday, Today and Tomorrow." *Working Paper - Institute of Advanced Manufacturing Sciences* (2000).
- Parkinson, S.T. "Successful New Product Development - An International Comparative Study." *R&D Management* 11, no. 2 (1981): 79-85.
- Production, Metalworking. *The Fifth Survey of Machine Tools and Production Equipment in Britain*. London: Morgan Grampian, 1983.
- Raiser, Ernst. *Wie das erste numerisch gesteuerte Bearbeitungszentrum bei Burkhardt+Weber entstand* (1) [Compact Disk]. Burkhardt+Weber Gruppe, 2001 [cited].
- Reintjes, Francis J. *Numerical Control: Making a New Technology*. Edited by J.R. Crookall, Milton C. Shaw and Nam P. Suh. Vol. 9, *Oxford Series on Advanced Manufacturing*. New York, Oxford: Oxford University Press, 1991.
- Rendeiro, Joao O. "How the Japanese Came to Dominate the Machine Tool Business." *Long Range Planning* 18, no. 3 (1985): 62-67.
- Romeo, Anthony A. "Interindustry and Interfirm Differences in the Rate of Diffusion of an Innovation." *The Review of Economics and Statistics* 57, no. 3 (1975): 311-319.
- Schmookler, J. "Economic Sources of Inventive Activity." *The Journal of Economic History* 23, no. 1 (1962): 1 - 20.
- Schröder, Sascha. *Innovation in der Produktion: eine Fallstudienuntersuchung zur Entwicklung der numerischen Steuerung*. Edited by Günter Spur. Vol. 168, *produktionstechnik - Berlin, Forschungsberichte für die Praxis*. München, Wien: Carl Hanser Verlag, 1995.

- Schwab, Gerhard. "Die Entwicklung der deutschen Werkzeugmaschinenindustrie von 1945 - 1995." 1 - 62. Frankfurt am Main: Verein Deutscher Werkzeugmaschinenfabriken e.V., 1996.
- Sciberras, E., and B.D. Payne. *Machine Tool Industry*. Edited by The Technical Change Centre. 1 ed. Vol. 1, *Technical Change and International Competitiveness*. London: Longman Group Limited, 1985.
- Spur, Günter. *Die Genauigkeit von Maschinen: eine Konstruktionslehre*. 1 ed. München, Wien: Carl Hanser Verlag, 1996.
- . *Vom Wandel der industriellen Welt durch Werkzeugmaschinen*. Edited by Verein Deutscher Werkzeugmaschinenfabriken e.V. München, Wien: Carl Hanser Verlag, 1991.
- Spur, Günter, Dieter Specht, and Sascha Schröder. "Case B: Die Numerische Steuerung (NC-Machine Tools)." In *Culture and Technical Innovation: a Cross-Cultural Analysis and Policy Recommendations*, edited by The Academy of Sciences and Technology in Berlin (Working Group: Culture and Technical Innovation), 621 - 735. Berlin: Walter de Gruyter, 1994.
- Steeds, W. *A History of Machine Tools 1700 - 1910*. Oxford: The Clarendon Press, 1969.
- Teresko, John. "Emerging Technologies." *Industry Week*, Mar 5, 2001 2001, 17 - 19.
- Tschätsch, Heinz, and Werner Charchut. *Werkzeugmaschinen: Einführung in die Fertigungsmaschinen der spanlosen und spanenden Formgebung*. 6 ed, *Das Fachwissen der Technik*. München, Wien: Carl Hanser Verlag, 1991.
- Tushman, Michael L., and Philip Anderson. "Technological Discontinuities and Organizational Environments." *Administrative Science Quarterly* 31, no. 3 (1986): 439-465.
- Unger, Harlow. "Industrial America: Strategies for Recovery in Machine Tool Industry." *Industrial Management* 9, no. 4 (1985): 13.
- USDoC. "Census." US Department of Commerce, 1959 - 1968.
- VDMA. "Kennzahlenkompass." Frankfurt am Main: Verband deutscher Maschinen- und Anlagenbau e.V., 1993.
- VDW. "The German Machine Tool Industry in 1999." Frankfurt am Main: Verein Deutscher Werkzeugmaschinenfabriken e.V. (VDW), 1999.
- . "The German Machine Tool Industry in 1999." 1 - 52. Frankfurt: Verein Deutscher Werkzeugmaschinenfabriken e.V., 1999.
- VDW, WS Atkins Management Consultants in assoc. with Ifo-Institut. "Strategic Study on EC Machine Tool Sector." 43: VDW.
- Vonortas, Nicholas S., and Lan Xue. "Process innovation in small firms: case studies on CNC machine tools." *Technovation* 17, no. 8 (1997): 427-438.
- Wagoner, Harless D. *The US Machine Tool Industry*. Cambridge, MA: The MIT Press, 1966.
- Wight, Oliver W. *Manufacturing Resource Planning: MRP II: Unlocking America's Productivity Potential*. New Jersey: Englewood Cliffs, 1982.
- Witte, Horst. *Werkzeugmaschinen: Grundlagen und Prinzipien in Aufbau, Funktion, Antrieb und Steuerung spangebender Werkzeugmaschinen*. 7 ed, *Kamprath-Reihe*. Würzburg: Vogel Buchverlag, 1991.

Xunxian, Liang. "China's Machine Tool Industry." *The China Business Review* 8, no. 6 (1981): 30 - 36.

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